Investigation of Multi-Robots Food Foraging Efficiency with an Artificial Pheromone System

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Abstract

In nature, the pheromone released by social insects is crucial for communication, which has become a rich inspiration source of swarm robotics. By utilising the virtual pheromone in physical swarm robot system, we can coordinate individuals and simulate behaviours of social insects. This thesis aims to investigate two influences, i.e., the leader and the wind effects on multi-robots' food foraging efficiency in an artificial pheromone system, wherein the pheromone is represented by light spots or trails on a TV screen. To investigate the leader effect, we remotely controlled a robot agent as a leader to guide other wandering agents to reach a food source with persistent virtual pheromone and then aggregate around it; the released pheromone by the leader could be sensed by other mates so that triggering following behaviour. We compare the aggregation efficiency with the scenarios without a leader robot agent. After that, we simulated wind effects on the virtual pheromone affecting its evaporation and diffusion. The experimental results demonstrate that without interacting with the leader, the aggregation efficiency is highly depending on start positions of follower agents within each experiment. The potential of using the leader interaction with the other robots can improve the swarm efficiency under the same experimental setting. Moreover, the experimenting results of wind effects on the artificial pheromone system and the food foraging simulation demonstrate the wind has the power to influence the food foraging efficiency, which cannot be ignored. This research indicates that the leader and the wind effects are important factors affecting the pheromone-based swarm efficiency.

Keywords: artificial pheromone, multi-robots, food foraging, wind effect, Leader following.

Acknowledgement

This research was not and could not be complete only by myself with my own skills. Therefore, I really would like to thank those persons who supports me well during its developing. Firstly, I deeply appreciated my supervisors, Professor Shigang Yue and QinBing Fu. They guided me throughout the development of this research course and supports me well with information about different methods towards different situations.

Because I have changed the research area in the end of September last year. Therefore, I would like to express gratitude to Professor Shigang Yue to support from helping me to understand how the basis of the Colias, and how to use it as a tool of experimenting to investigate different areas in artificial intelligence.

Finally, I sincerely thanks to my parents who supports and gives me the opportunity to continue studying in the University of Lincoln. It's been a challenge task and it's been fun to enjoy the study at the University of Lincoln computer science postgraduate course. And thanks to all the PhD students in the CIL group for helping me to solve different tasks and guides me with their knowledge and experiences.

Contents

Chapter 1. Introduction

With the implementation of different abilities of micro-robot platforms to replicate the real-world animals' behaviours, it is more accessible and comfortable for us to control multiple robot agents at the same time. In real world, animals adopt various kinds of sensors and methods for communicating with mates. More specifically, insects, like ants, use a lot of different chemical signals or pheromones to interact within the dynamic world, disseminating information of predators and food sources and etc. These naturally developed communication methodologies are always attractive to computational modellers and engineers for building artificial communication systems with similar characteristics to benefit real-world applications. However, it is still a challenging problem to simulate these behaviours and spread them widely to people using multi-robots in case of the high price of hardware and the complex control systems. In 2014, inspired by ants, Arvin (Arvin et al., 2014) developed a new method to mimic pheromone-based communication in swarm robot behaviours. As a prominent case study leading this research direction, they used a leader following scenario to simulate the real-life insects' behaviours and modelled a virtual pheromone system as the communication methods to help multiple robot agents to complete different tasks. Building upon their work, this thesis aims to look deeper into the swarm efficiency of multi-robots in food foraging and aggregation simulation based on their proposed artificial pheromone system. More precisely, a TV arena was used as the experimenting platform carrying out all tests in this research. The virtual pheromones were projected onto the TV screen as grey scales. The micro mobile robot platform used in this research possesses light sensors which are crucial to sense the pheromones with different densities represented by distinct grey levels.

This research takes into account two main factors for investigation, i.e., the leader and the wind effects on food foraging and swarming efficiency. Firstly, differently from the previous research, the leader robot agent was remotely controlled by the researcher aiming to conduct other foraging agents to reach a certain food source, more efficiently. This part of research compares the situations of food foraging and aggregation around the food source with and without a manually controlled leader agent robot. The only index is the aggregation completion time of each process recorded with a t=0s timer. The leader is a pre-scripted micro-robot controlled by a host PC through built-in Bluetooth function for communication and motion control. Therefore, the researcher can directly control the leader, which release pheromones to attract other agents to follow and arrive at the food source.

Under the same experimental metrics and continuing with the former idea, this thesis investigates also the wind effects on virtual pheromones released by both the leader robot agent and the food source. The comparative experiments inspected the key parameters in formation of wind effects: evaporation, diffusion and influence. The systematic and comparative experiments demonstrate two main achievements of this research: (1) the major role of leader robot in pheromone-based food foraging simulation has been proved, compared to the scenarios without a leader, which demonstrates the potential significance of leader effects in shaping swarm collective behaviours; (2) like the real chemical pheromone dissemination in nature, the wind effects cannot be disregarded in constructing artificial pheromone communication system; and moreover, despite the wind influence on swarming efficiency, the leader can also well guide the normal agents forming following and aggregation behaviours in the arena tests.

1.1 Objectives:

Those are the main objectives of this work:

- Understanding how to use the artificial pheromone to communicate with each other.
- Look into the leader effects on food foraging and aggregation behaviours.
- Plotting a strategy for differentiating the food and the leader pheromones in order to trigger different robot behaviours completing leader following and aggregation around a certain food source.
- Designing a remote-control system for the communication between the host and the leader robot to complete different tasks.
- Statistical analysis of comparative experiments results to demonstrate the leader and wind effects on swarming efficiency using time metrics.

1.2 Contributions:

By addressing the listed objectives, this work results in the following contributions:

- Background research and systematic review in the areas of 1) applications based on the Colias (Arvin et al., 2014) micro mobile robot used in this research, 2) swarm robotic behaviours and artificial pheromone systems with applications.
- A Bluetooth based remote communication system implementation and a User Interface (UI) design for interacting with the leader robot agent and controlling its motion in real time in arena tests.
- Systematic experiments to investigate the leader effects on food foraging and aggregation efficiency in arena simulations.
- Investigation of the wind influences on leader following and aggregation.

1.3 Thesis Outline

The remainder of this thesis is structured as follow: Section 2 describes related work in Colias robot platform design, Colias robot vision-based applications, pheromone theory and artificial systems, swarm robotics and multi-robot's localisation systems. Section 3 introduces the methods and models which used in this thesis. Section 4 demonstrate the implementation detail of this thesis and will mainly focus on five sub-sections. Section 5 exhibits the settings of the experiment, the results of 2 sets of experiments and discuss the results from those sets of experiments. Lastly, section 6 concludes this thesis and describes the plan for the future works.

Chapter 2. Literature Review

This section reviews related works in the areas of 1) design and applications of the micro mobile robot used in this thesis, 2) artificial pheromone system in swarm robotic research.

2.1 The Colias Micro-Robot Platform Design

In this sub-section, we will go through two parts of related areas: 1) the hardware configuration of the Colias micro-robot platform; 2) the applications by using the Colias robot including vision-based models' implementation.

2.1.1 Hardware Configuration

In order to controlling a large number of micro-robots to solve common complex tasks has become the core of designing the swarm robotic platform. However, due to the number of micro-robots needed, the hardware complexities, cost of the robot platform and the current research is mostly performed by simulation software, but the results from the simulation sometimes can be inaccurate due to the poor modelling. Under those conditions, Arvin (Arvin, et al., 2014) presents a new micro mobile robot named `Colias', which is a new low-cost, open-platform, autonomous micro-robot designed for swarm robotics education and research. It is also supported by software development tool. The robot architecture is illustrated in Figure 1, and Figure 2 (Arvin, et al., 2014). By using this low-cost (About £25, as shown in Table 1.) robot platform, and the abilities can hugely increase the performance of each experiment in different swarm robotics researches. As listed in Table 1 the Colias is just £25, and it has many different sensors which means it has more potential in different situations, and also the sensors are embedded on the micro-robot platform, this helps the Colias in different situations, and also because of the sensors are embedded on the micro-robot platform, there is enough spaces to add additional add-on to the robot to make it more feasible for different tasks.

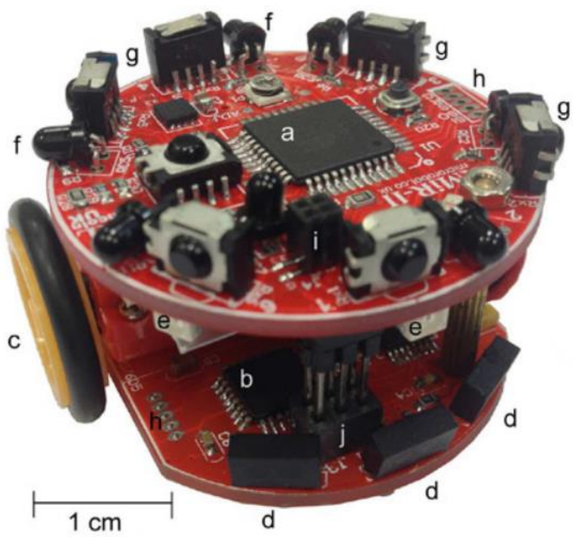


Figure 1: Colias micro-robot platform (adapted from Arvin et al., 2014) There are two processors in this model, the first is the upper board processor (a); and the 2nd processor is located in the lower board and it is for the motion and power management (b); (c) is the 2.2 cm diameter wheels; there are 3 proximity (bumpers) sensors in the font (d); (e), (f), (g) are IR transmitters, phototransistors and decoders respectively. (i) and (j) are the links to the next platform.

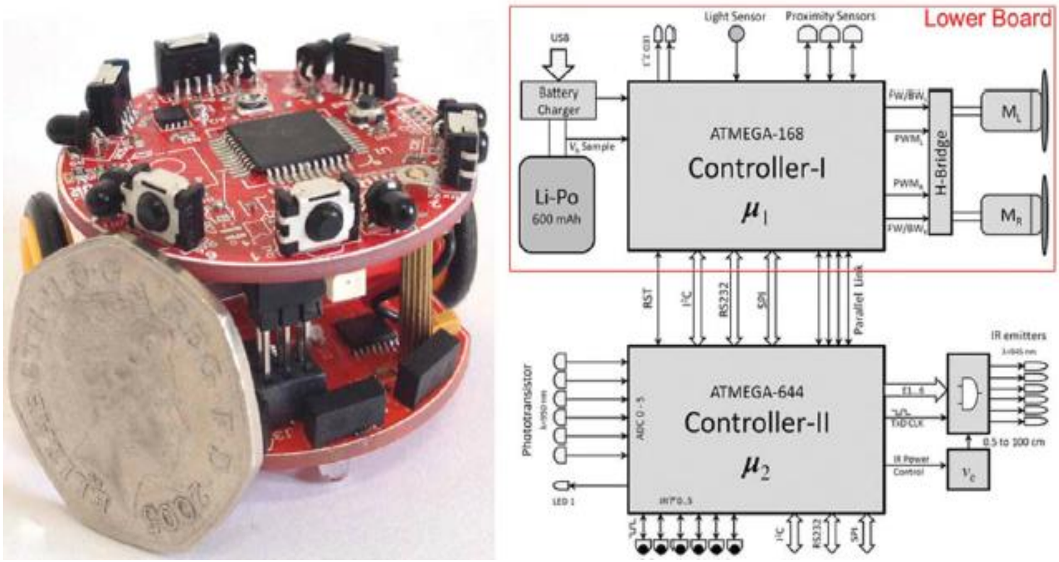


Figure 2: The size of the Colias micro-robot platform is the same (adapted from Arvin et al., 2014).

Table 1: A Comparison between different micro-robot platforms

Robot	Cost	Sensor	Motion/Speed	Size	Autonomy
Colias	£25	Distance, light, bump, bearing, range	Wheel, 35 cm/s	4 cm	1-3h
AMiR	£65	Distance, light, bearing	Wheel, 10 cm/s	6.5 cm	2h
Alice	N/A	Distance, camera	Wheel, 4 cm/s	2.2	10h
Jasmine	£80	Distance, light, bearing	Wheel, N/A	3 cm	1-2h
E-Puck	£580	Distance, camera, bearing, accele, mic	Wheel, 13 cm/s	7.5 cm	1-10h
Kobot	£800	Distance, bearing, vision, compass	Wheel, N/A	12 cm	10h
Kilobot	£75	Distance, light	Vibration, 1 cm/s	3.3 cm	3-24h
R-one	£220	Light, IR, gyro, bump, accelerometer	Wheel, 30 cm/s	10 cm	6h
SwarmBot	N/A	Range, bearing, camera, bump	Wheel, 50 cm/s	12.7 cm	3h
Cellulo	N/A	Camera, capacitive touch	Ball wheel, 20 cm/s	7.5 cm	1-2h
Droplets	N/A	Light	Vibration, N/A	4.4 cm	24h+
Mona	£100	Distance, bump, range, RF	Wheel, 5 cm/s	6.5 cm	Perpetual
R-One	£200	Light, IR, gyro, bump, accelerometer	Wheel, 30 cm/s	10 cm	6h

Despite the success, there are many issues in different areas of Colias micro-robot platform. In the first few years of designing miniature mobile robots, many issues were related to the power consumption for the micro-robots to perform complex tasks with accurate results. In the past, the micro-robots require employing extra hardware to be able to estimate the correct position. However, it is tough to employ any extra hardware, due to the hardware limitations. Therefore, Arvin and Bekravi (2013) have presented a new Encoderless position estimation with error correction techniques which is called Odometry techniques to replace the old method: the position estimation of the Colias is depending on the speed of the left and right wheels (Arvin et al., 2014). By using the trajectory of the robot is divided into several displacements over a short span of time (δ_t) (Figure 3). Therefore, the position of the robot is calculated within a short period using the speed equations of the robot's wheel. Also, by adding the error correction to the system increase the performance in an average error of 0.5 mm to 2mm in different conditions of the environment. With the new Odometry techniques on, there is no need to add any extra sensors.

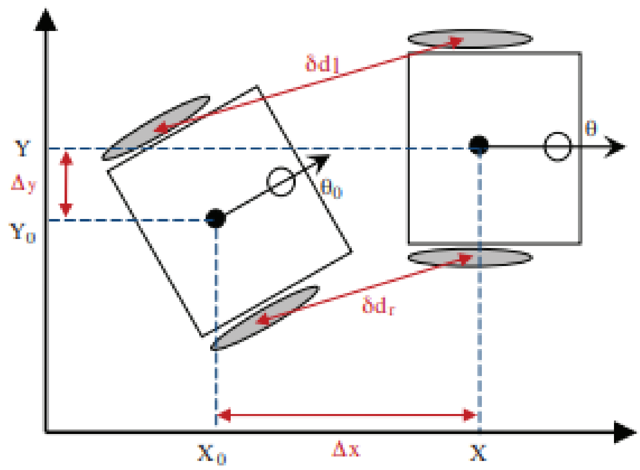


Figure 3: Movement of the mobile robot in a time span (δ_t), *Δy* and *Δx* the distance of travelling (adapted from Arvin and Bekravi, 2013).

There are a lot of different sensors that the Colias micro-robot platform uses, mainly can be separate into these parts: the first part is embedded on the Colias Base Unit (CBU), the second part is embedder on the Colias Sense Unit (CEU). In these two platforms, in contains the abilities of how the Colias is able to complete different tasks. For example, the bumper which located in the front of the Colias Base Unit (as shown in Figure 4), the ability of those are used for avoiding obstacles when the objects or other Colias are too close to each other, the bumper will send a signal to the Colias motor and let the Colias to have certain movement to avoiding the incoming objects. There are several LEDs around the CBU and CEU, all of them has different role to help the researchers understand what kind of commands has executed in the process. Such as, in the Colias Base Unit, it has the front proximity (bumper) sensors; there is two light sensors which located between the front bumper and the Atmega 168 model. In this thesis's food foraging experiment, if the followers find the target pheromone, this light sensor will light up with a red light, this indicates the target is successfully found (Arvin et al., 2014 and Hu et al., 2018).

It has been a lot of different versions of updates, since the micro-robot platform Colias first time present in 2014 by Arvin and his colleagues (Arvin et al., 2014). It has been upgraded with Encoderless position estimation and error correction techniques to enhance its ability to perform the common complex tasks in real-life (Arvin and Bekravi, 2013). Then the University of Lincoln Computational Intelligence Laboratory (CIL) has implemented a bio-inspired visual module for the Colias platform to be able to 'see' the environment and provides the information to the researchers (Arvin and Bekravi, 2013). Last year, thanks to the implementation to the Colias since it first release in 2014. The new edition Colias now has three units (Figure 4), the Colias Base Unit (CBU) (Figure 5), the Colias Sense Unit (CSU) (Figure 6), the Colias Extension Unit (CEU), and the Figure 7 shows the structure of CBU and CSU and the interaction in those modules. The Colias IV has been released, as an affordable micro-robot platform with bio-inspired vision module. The vision system is the core sensing module which is commonly used in any of the robot platforms. However, with the hardware limitations, the current visual ability is seldom applied or with reduced resolutions and functions (Hu et al., 2018). In this research, a micro-scale visual system has been presented with the ability of bio-inspired collision detection. The challenges at the beginning are how to process images in real-time under the limited computational resources and the limited wireless connections between the host and the robot.

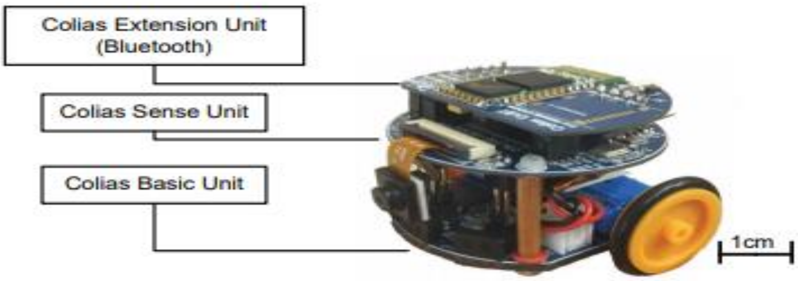


Figure 4: The three units of the Colias IV model (adapted from Hu et al., 2018): This is a complete Colias IV model which has three different units. The top layer which has the ability for human interaction. You can use different command lines to control the robot's action through a connection build in the extension unit by using the Bluetooth serial port.

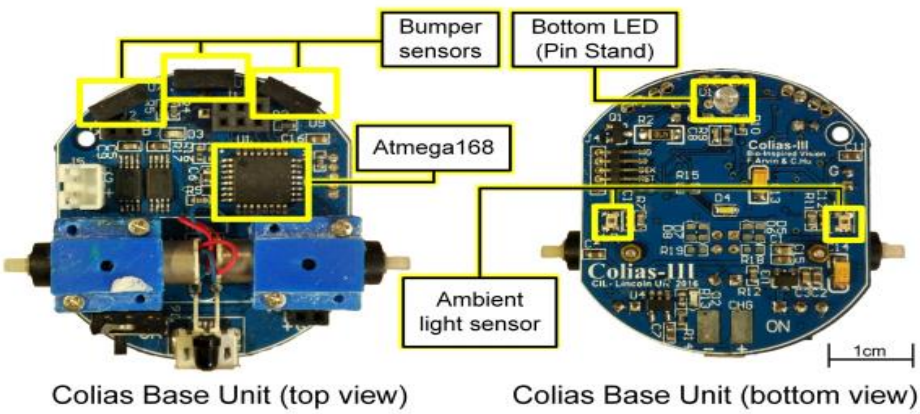


Figure 5: The Colias Base Unit (adapted from Hu et al., 2018): this is the base unit of the Colias, the bumper is used for the detecting and avoiding incoming objects; the ambient light sensor is used for detecting different light sources. For example, in pheromone trail following scenario, the different readings pick up from left or right will be compared, if the left one is greater than the right, then the robot will turn to the left side.

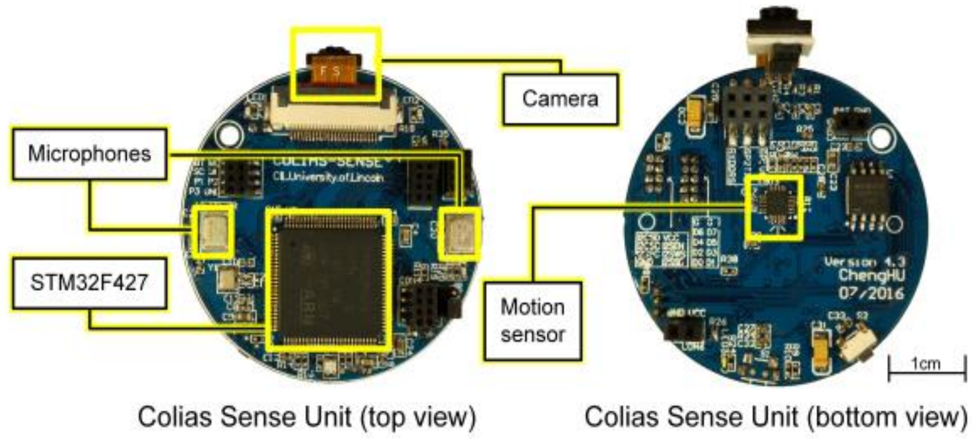


Figure 6: The Colias Sense Unit (adapted from Hu et al., 2018): In this unit, there are two main parts; the first one is the camera, this is a low-cost camera but have enough ability to record and capture the images from a set of movement. Also, the robot has the ability to use LGMDs for visual tasks. The second one is the motion sensor; this sensor helps the Colias to understand the commands from the Colias Extension Unit and execute them through this sensor and give to the base to run.

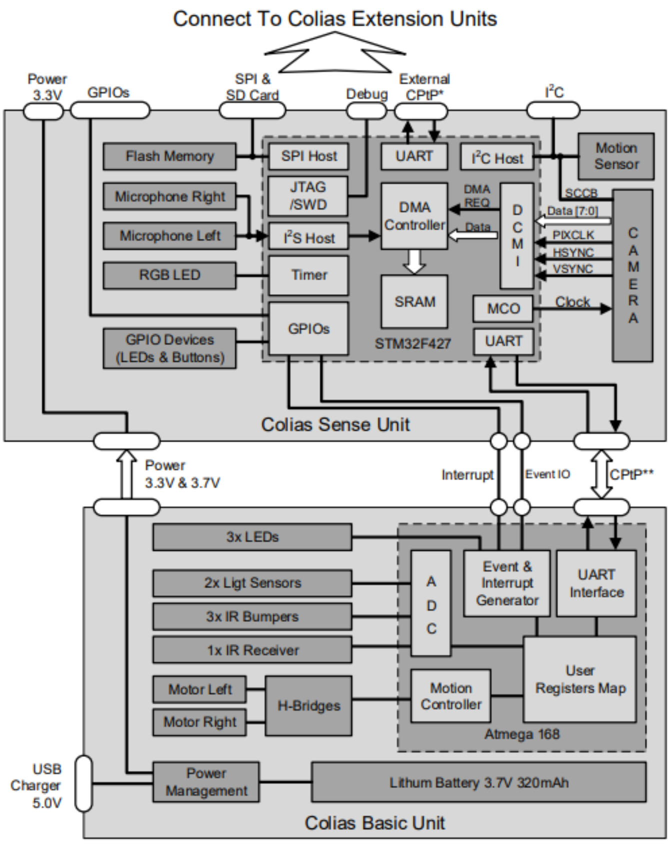


Figure 7: The interaction between CBU, CSU and the CEU (adapted from Hu et al., 2018). This is the layout of the Colias IV unit, in this diagram you can easily see different parts of the Colias components relation with others.

2.1.2 Applications

In case of vision-based robot platforms, the Colias robot has the smallest size in the literature so far. Since the vision sensor is the most significant and advanced one in the Colias micro mobile robot, the vast majority of researches have been focused on development and implementation of bio-inspired dynamic vision systems using the Colias's visual sensing modality. In 2014, the Computational Intelligence Lab (CIL) at the University of Lincoln had presented a developed bio-inspired vision system for low-cost mobile micro-robots. In their research, the vision system is inspired from the locusts in detecting the fast approaching objects, and from the locusts use a wide-field visual neuron called the Lobula giant movement detector (LGMD) (Figure 8 the LGMD model) to respond to imminent collisions (Hu et al., 2014). As the difference showing in Figure 9, a) is the original image; b) is the when the image process through the E-layer, where the hand and the jar stands out; c) is the when the image process through the G-layer, the image have been enhanced. By adding this new visual module onto the top of the mobile micro-robot. The results from several experiments indicate that the developed extension module and the inspired vision system are feasible for obstacle avoidance and motion control. The research conducts the visual module has strong robustness to adopt different environment and even in real-world applications. FFI is the Feed-Forward Inhibitory. As Figure 10 shows, the trajectory shows by using the

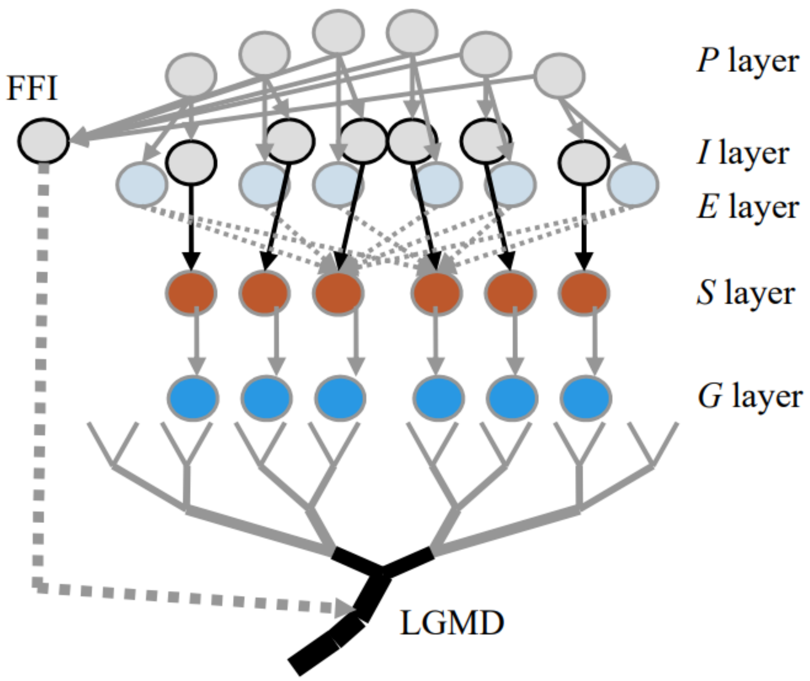


Figure 8: The LGMD model (adapted from Hu et al., 2014), the P-layer is Photoreceptor, the I-layer is Inhibitory, the E-layer is Excitatory, the S-layer is Summing, the G-layer is Grouping, the FFI cell is feed-forward inhibitory and the LGMD cell.

embedded version system can potentially helps the robot to navigate through a ‘forest’ environment.

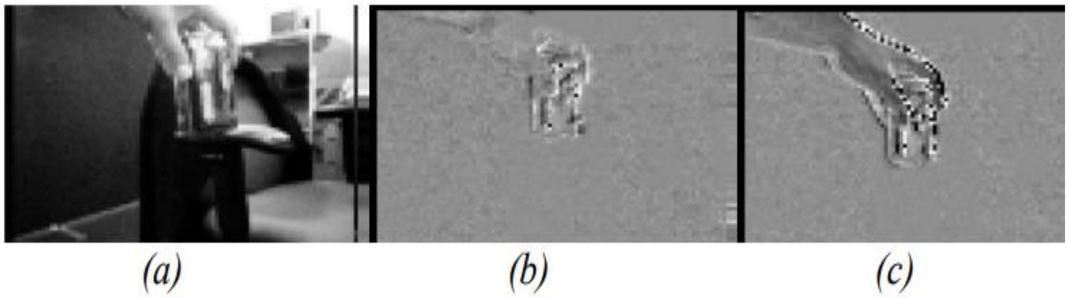


Figure 9: The image shows: a) the original image, b) when the image pass through P-layer, the image has been the background detail is inhibited, but the hand and the jar stand out; c) the output of G-layer, the details of the hand and the jar are enhanced (adapted from Hu et al., 2014)

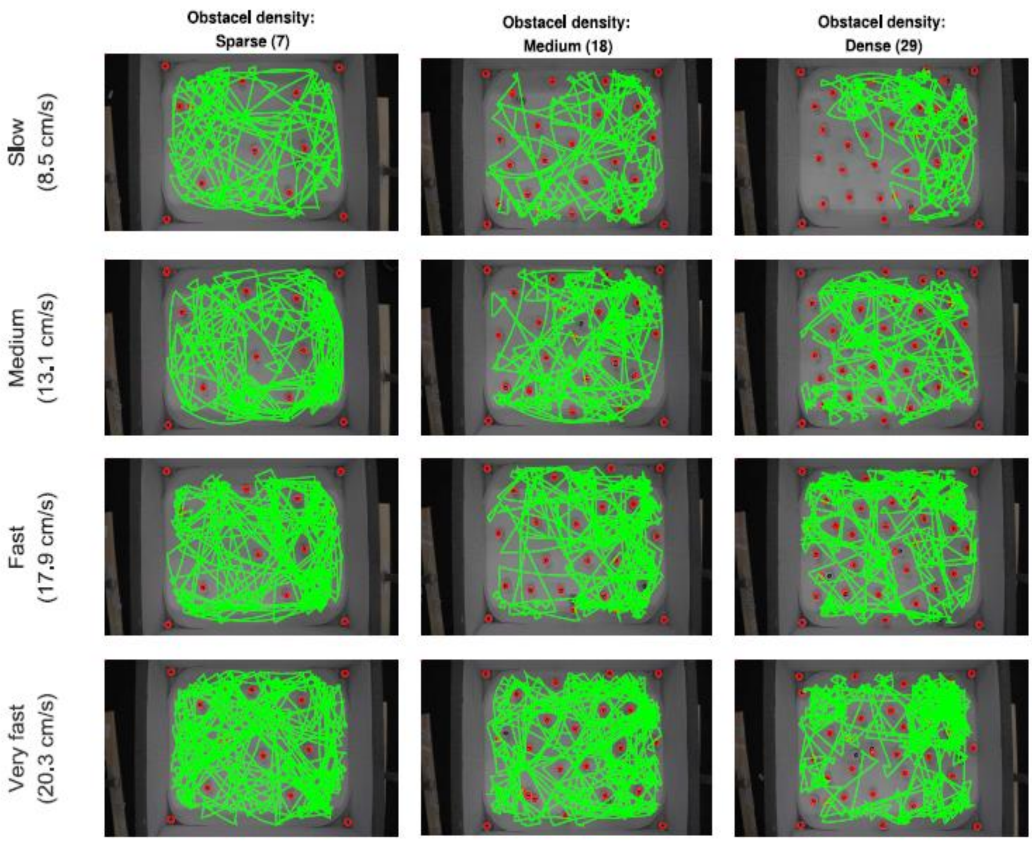


Figure 10: In this image, a top-down visualisation of the experiments of the Colias trajectories in a ‘forest’. The green lines represent trajectory of the robot and the red points are the initial points of the obstacles (adapted from Hu et al., 2017). These experiments prove the Colias micro-robot has the ability to continuously navigate through a complex environment with very successful rates.

Motion perception is a critical capability to determine a variety of aspects of insects' life. A lot of different motion detectors have been identified in the insects' visual pathways including the ability to avoiding predators and foraging. In a recent paper (Fu et al., 2019), it reviews the computational motion perception models originating from biological research of insects' visual system. Through the studies of different models, they summarised the methodologies that generate different direction and size selectivity in motion perception. The reviews have summarised different methodologies including lateral inhibition mechanisms and non-linear computation to implement different selectivity. In the conclusion of their review, they conclude that there is a high potential of those dynamic vision systems in building neuromorphic sensors for volume production in the future (Fu et al., 2019).

In 2016, the new implementation of the selected neuron model by a low-cost ARM processor as part of a composite vision module had been presented (Hu et al., 2016). The developed system performs all image acquisition and processing independently. With different simulations and real-world experiments were carried out, the potential of the bio-inspired system as a reliable, robustness and low-cost embedded module for autonomous robots (Hu et al., 2016). A reliable, low-cost, compact and low power consumption visual collision detection and avoidance system have been presented in their research (Hu et al., 2016).

There are two LGMDs visual systems has been identified in the collision selective neuron during years of studies; they both serve different parts in a different age of the locust. In 2017, Fu presented a new binocular neuronal model to the collision selectivity neuron by combining both LGMD1 and LGMD2's functionalities show in Figure 11. The results from combining the two systems demonstrate: by utilising the micro-robots with the new model has potential benefits to the swarm robotics researches. The different collision selectivity between LGMD1 and LGMD2 models, which fulfil corresponding biological researches. From the further researches on the model, Fu has found out that the LGMD2 performs more robustly compared to LGMD1 for ground robots in daylight navigation. If adding a new hybrid system with similar structures, the collision selectivity could be further enhanced (Fu, 2017). This study opens several directions for future works that are related to the visual systems.

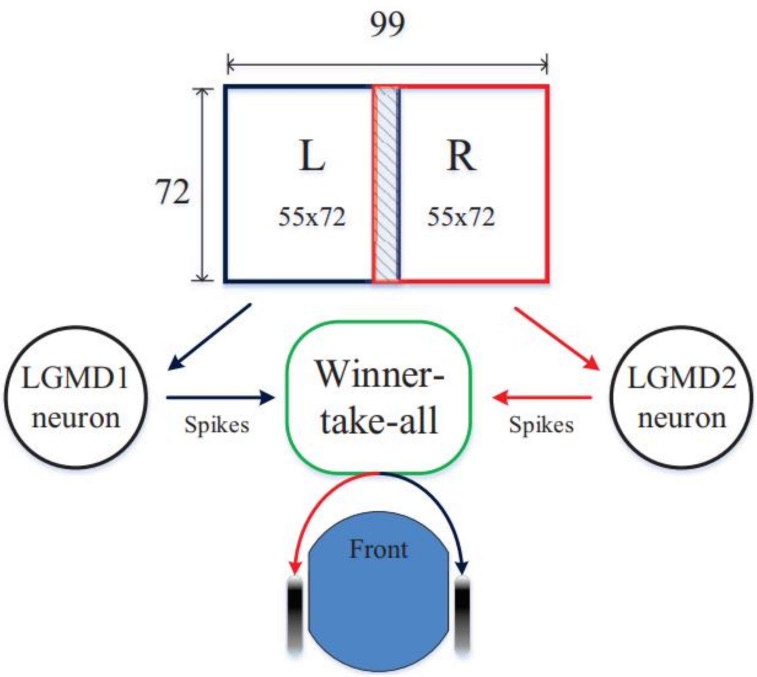


Figure 11: The illustration of image processing in the visual modality of the micro-robot and the directional motion control strategy with a bilateral pair of LGMDs neuron models (adapted from Fu et al., 2017).

The ability to quickly and robustly detecting incoming obstacles and avoiding them is crucial in simulating the micro-robots in real-life tasks. The potential advantages of using the collision detection and obstacle avoidance in the ground- robotic vision system is massive. The Computational Intelligence Laboratory at the University of Lincoln (CIL) have presented a novel collision selective visual neural network inspired from LGMD2 neurons in the juvenile locusts that only selenite to detect looming dark objects against a bright background in depth, represents swooping predators in 2017 (Fu et al., 2017). There are two significant contributions in this research, first is to enhance the collision selectivity in a bio-inspired way and realising the revealed specific characteristics of LGMD2; second, is to apply a neural network to help near range path navigation of an autonomous ground robot in the arena.

In 2015, several experiments were performed to the locust's visual neuron, the lobula giant movement detector (LGMD). After further research on the locust's visual neuron, the visual neuron now has been separated into two different systems, the LGMD1 and LGMD2. In Fu and Yue's research (2015), they proposed a new model for the LGMD2, in order to emulate its predicted bio-functions, moreover, to solve the mechanism of ON and OFF cells (Figure 11 and 12), as well as bio-inspired nonlinear functions to achieve the collision selectivity. In their experiments with the new model of LGMD2, the feasibility and robustness of LGMD2 system, which could also be further used to be a collision detector in other mobile robot platforms for path exploring and motion planning even in a real-time environment (Fu and Yue, 2015). The arena tests result as Table 2 shows the results were based on the ON-OFF method presented in 2015 by Fu (Fu et al., 2015), the test is based on the collision recognition ability of LGMD2 neural network in an arena with 10~20 obstacles (Fu et al., 2016).

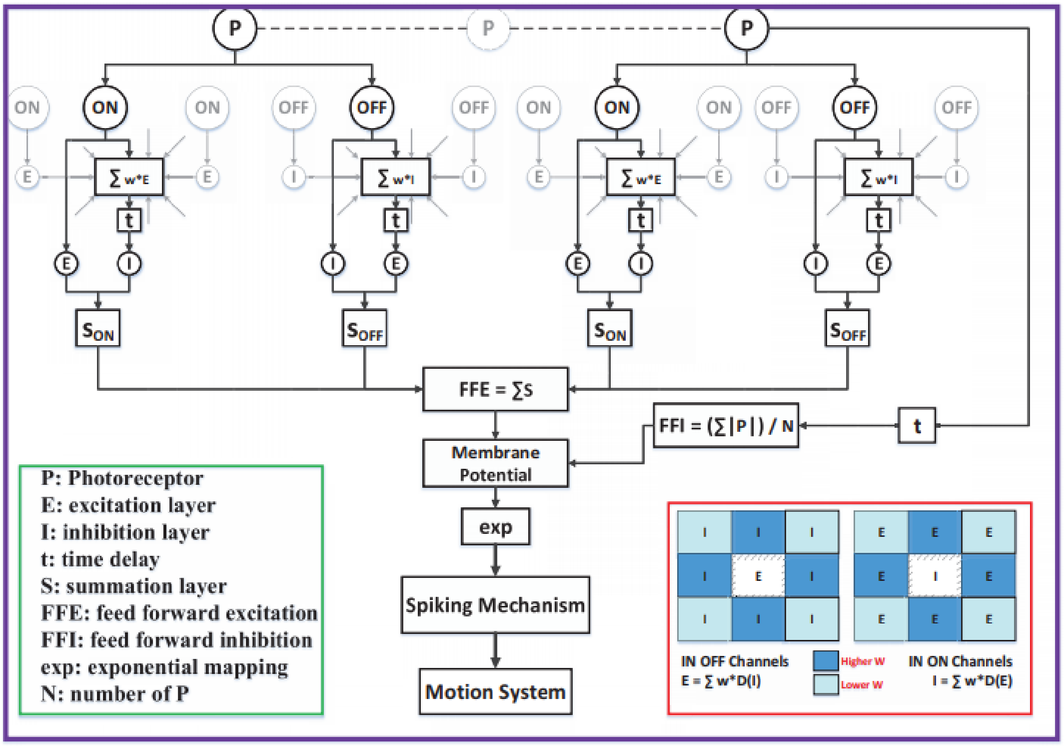


Figure 11: The LGMD2 computational model, the signals from the P-layer are divided into 4 kinds, then separately process in ON and OFF channels (adapted from Fu et al., 2016).

Table 2: This table shows the successful rate of arena tests under four candidates firing thresholds (T_{sp}) (adapted from Fu et al., 2016).

MD – Miss Detection, CD – Correct Detection
Success Rate – $SR = [CD/(MD + CD)]\%$

T_{sp}	MD	CD	SR
320	7	58	89.2%
300	3	61	95.3%
280	6	60	90.9%
260	10	55	84.6%

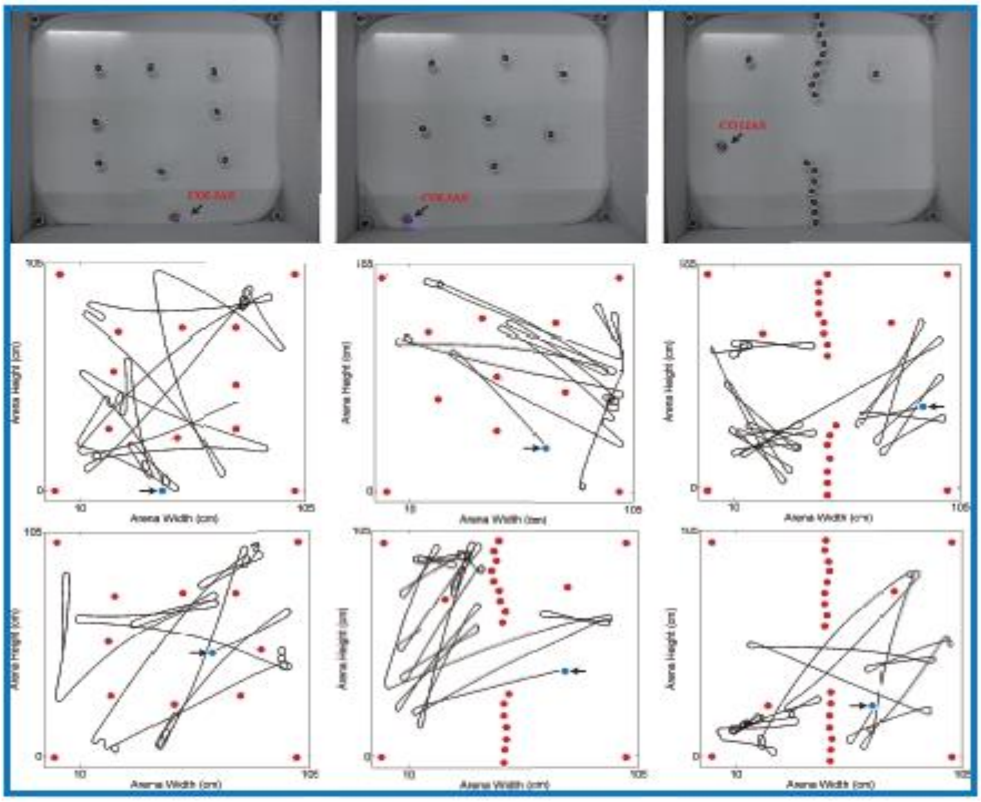


Figure 12: This table shows the potential of using the proposed method could increase the success rate by using the ON-OFF method. The second image is a tap-down view of the experiment arena, and the trajectory of the robots' path. Depends on the results presented by Fu (Fu et al., 2016), the proposed method has the potential of solving the defects of LGMD1 visual system (adapted from Fu et al., 2016).

Motion tracking can be used in the different area of robotics vision researches. In 2018, a new novel modelling of dynamic vision system inspired by Drosophila physiology for mimicking fast motion tracking and closed-loop behavioural (in Figure 13) response to fixation has been presented by Fu (Fu et al., 2018). The proposed model realised an embedded system in an autonomous micro-robot which has limited computational resources (Fu et al., 2018). From the experiment results, the effectiveness, robustness and efficiency of this approach simulating insect visual fixation behaviour.

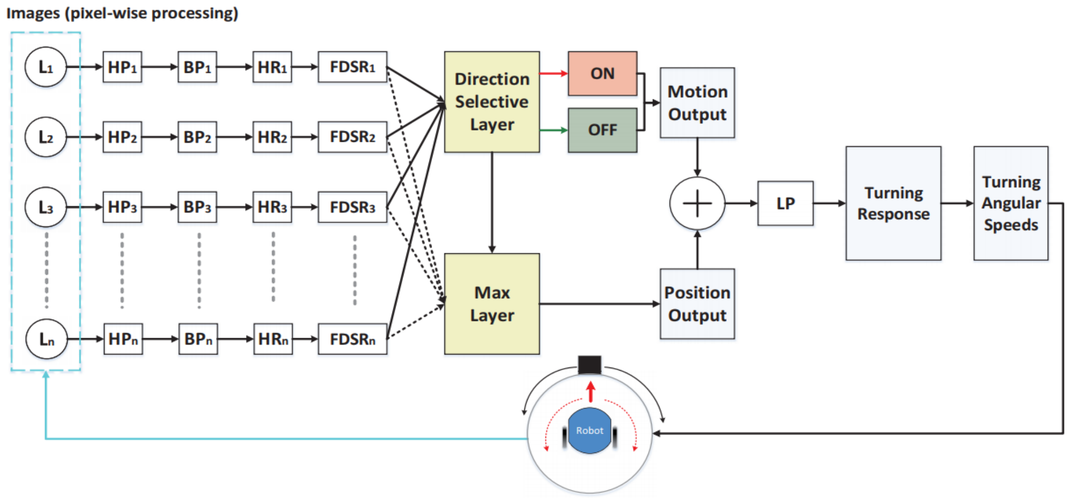


Figure 13: This is a proposed embedded vision system consists of ON and OFF and position pathways and a hybrid control for guiding robot fast motion tracking and fixation behaviours. (n) indicates the total amount of photoreceptors in the first layer; L is the pixel-wise grey-scale luminance; HP is for High-Pass, BP is for Band-Pass, and HR is for Half-wave Rectifier (adapted from Fu et al., 2016).

A hybrid vision-based robot control strategy called finite state machine (FSM) (Figure 14) was presented in 2018 for micro ground robots by mediating two vision models from mixed categories: the bio-inspired collision avoidance model and a segmentation-based target following model. The ability of FSM is the model can switch behaviours adapting to the acquired visual information; this enhances the ability for the micro-robots to be able to run visual models with more complexity. In this new model, there are two visual models has been presented, the bio-inspired collision detection neural model and a colour-sensitive target following algorithm. Both systems are computationally efficient and stable to be implemented on a microprocessor (Hu et al., 2018). As Figure 15 shows, the robots with the embedded hybrid vision model influences that robots tend to aggregate at the darker zones rather than the brighter zones regardless the different group sizes. The main factors of this selective behaviours are because of the cluster size and environment darkness (Hu et al., 201).

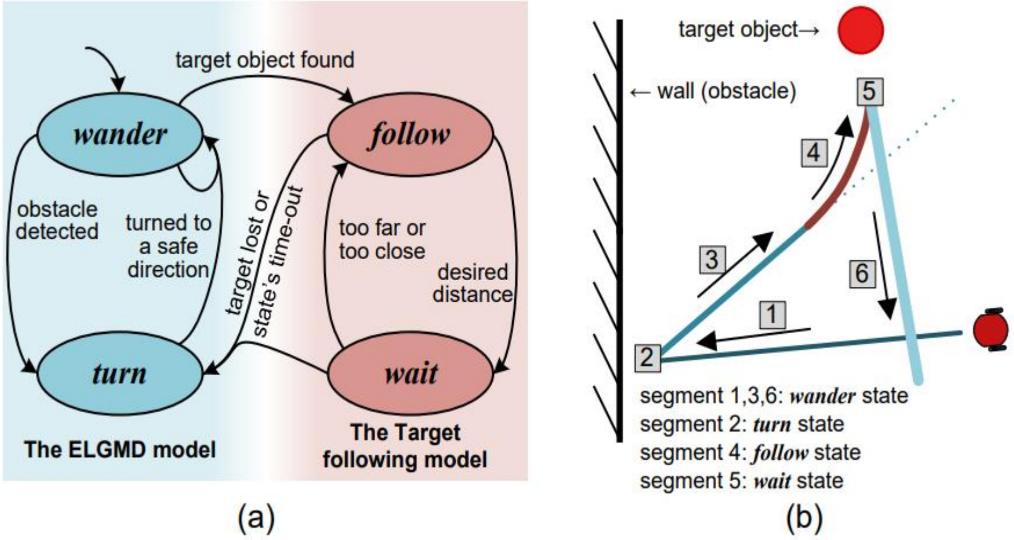


Figure 14: The proposed finite state machine to incorporate the two visual models: a) this is the illustration of proposed FSM; whose initial state is the wander state; b) The illustration of a typical scenario controlled by this hybrid visual system. (Hu et al., 2018)

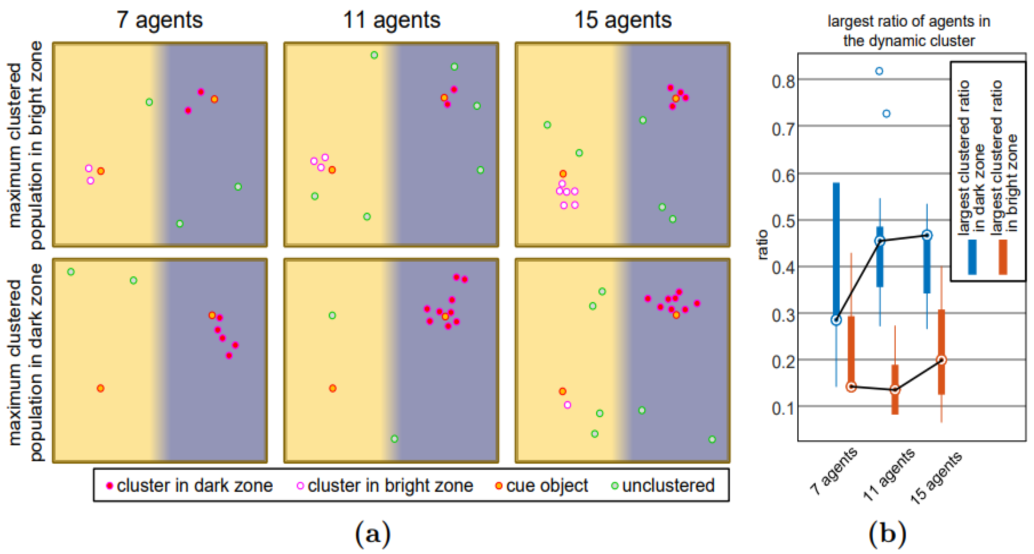


Figure 15: The images shows: (a)There are two different zones of clusters for multiple robots when the largest clustered population has reached in either zones (b) the largest cluster populations in all experiment trails. The darker zone always restrains robots longer, therefore, the darker zone has higher chances for more robots stop and meet. This experiment indicates the robot aggregation behaviour is affected by both cluster size and environment darkness (adapted from Hu et al., 2018).

Summary

In conclusion, though the current research in the Colias robot has been mainly conducted by visual modality, this micro mobile robot platform, possessing multiple sensing modalities and tiny size, has great potential in other research domains like swarm intelligence, more specifically, the simulation of social insects' behaviours, and even the city traffics and etc. By adding different equipment to the robot platform which can provide the abilities to complete even more complex tasks. Because of the Colias have the ability to communicate with another robot within the 2m range, therefore, it is possible to implement another way to increase the performance of guiding several robots to the dissertations in the future. Despite the success of the Colias micro-robot platform, there are still many areas that can be improved. For example, it is possible to create a new communication method for the robot to transferring data by using the Wi-Fi connections. This allows the robots to connect to the host and use the host computer can directly communicate to the robot and maintaining a stable communication and fast transferring data between the host and the robots. By doing this can potentially increase the Colias to have better resolutions and image quality from the camera and can achieve the ability of communication and transferring data in real-time.

2.2 Swarm Robotic Behaviours and Artificial Pheromone Systems

This section will focus on the related work in swarm robotics: 1) swarm robotic behaviours; 2) biological background of pheromone communication and artificial pheromone systems.

2.2.1 Swarm Robotics Behaviours

Swarm robotics is an approach to collective robotics that takes inspiration from the self-organised behaviours of social animals (Brambilla et al., 2013). In their review, they demonstrate that by using simple rules and local interactions, swarm robotics aims at designing robust, scalable, and flexible collective behaviours for the coordination of large numbers of robots. Many methods are used in communication between robots has been published in the review. Despite there are many works that have been done in the swarm engineering perceptive, there are still things waiting to be found. Such as the use of artificial pheromone communications etc.

In Mohan and Ponnambalam review (Mohan and Ponnambalam, 2009), swarm robotics has the remarkable abilities in finishing complex tasks cooperatively. Swarm robotics is a new approach to the coordination of large numbers of relatively simple robots, that are autonomous, not controlled centrally, capable of local communication and operates based on some sense of biological inspiration (Mohan and Ponnambalam, 2009). This review went through all the major areas, problems and algorithms in existing researches by 2009. In the review also talked about using the virtual pheromone to communicate in swarm robotics to coordinate together to achieve in many areas.

Baldassarre (Baldassarre et al., 2003) have conducted a set of experiments in simulating robots with the ability of aggregate and move together toward a light target in 2003 (as shown in Figure 16). In their research, they found out by exploiting the self-organising behavioural properties that emerge from the interactions between the robots and between the robots and the environment, are a powerful method for synthesising collective behaviour (Baldassarre et al., 2003).

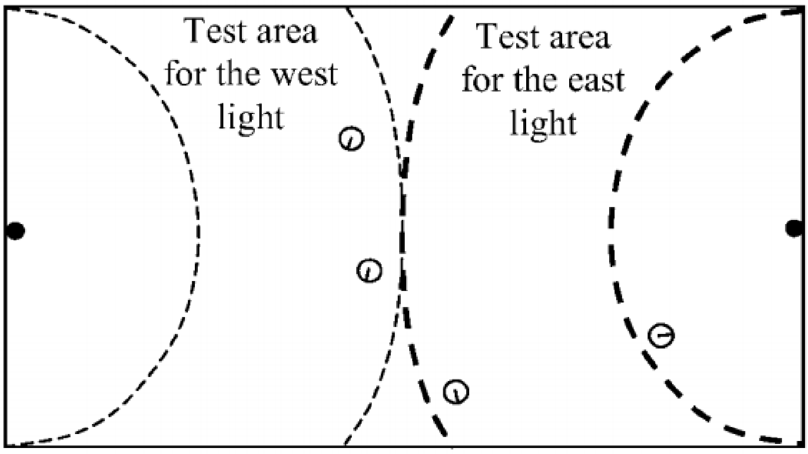


Figure 16: The simbots able to aggregate and move together toward a light target (adapted from Baldassarre et al., 2003).

In real life, the animals stay together when there is danger around them like elephant groups up against predators and protecting young babies; this kind of actions are called animal aggregations. In Grunbaum and Okubo 1986's idea is that social interactions cause the animal aggregation. In swarm robotics, by using the aggregation technique, we can simulate a lot of real-life actions such as food foraging and aggregation. That helps the other robots to find the food and use the model of aggregation to simulate when insects find the target and will stay together to achieve the collective animal behaviour in real-life, which Is one of the ways to socialising in insects. This method can benefit each group members from transferring information across the group and group decision making.

With this kind of inspiration from Grunbaum and Okubo, Marinoli (Marinoli et al., 1999) have presented an experiment with the collective animal aggregation with real robots in 1999. The paper has implemented in three different levels: the hardware implementation, the sensor-based simulation and a probabilistic model. By using the implemented clustering experiments, they found out to increase the coordination capabilities of robots, while keeping the team control fully decentralised, would be to introduce the local communication. Six years later, a new study has been conducted in the same area, Şahin and Soysal (Şahin and Soysal, 2005) presented a combination of four basic behaviours: obstacle avoidance, approach, repel and wait. Some of the aggregation behaviours are known to be facilitated by environmental clues; for example, flies use light and temperature. However, other aggregations are self-organised, like cockroaches that do not use clues but are instead result of new cooperative decisions (Şahin and Soysal, 2005). The study mainly focuses on self-organised aggregations since most of the micro-robots must be in some proximity of each other in many cases such as working together to finish complex tasks.

Şahin and Soysal (Şahin and Soysal, 2006) conducted studies with a self-organised aggregation of a swarm of robots in a closed arena. By using a probabilistic aggregation behaviour model inspired from studies of social insects, they proposed a macroscopic model for predicting the final distribution of aggregates in terms of the parameters of the aggregation behaviour, the arena size and the sensing characteristics of the robots. From the studies, that the self-organised aggregation does not require a cue from the environment or centralised control, it is an essential competence for swarm robotic system. The system is developed and used in a macroscopic model to predict the performance of the aggregation behaviour under different parameters of the swarm system. The results in this study are not satisfied due to the simulation cannot represent the power of the macroscopic model.

In 2007, Şahin and his colleague (Şahin et al., 2007) had presented a study to investigate two approaches for aggregation behaviour in swarm robotics systems: evolutionary method and probabilistic control. The first approach means the robots act reactively depending only on their inputs, and the controller is chosen to be a single-layer perceptron. However, the second approach uses a combination of three basic behaviours and obstacle avoidance, and those behaviours are arranged in two layers. Throughout the experiments, Şahin (Şahin et al., 2007) concluded that more complicated controllers could improve the performance of aggregation behaviour in this stage. By using multi-layers perceptron and other neural network, structures can lead to better aggregation performance (Sahin et al., 2007).

Aggregation is a common pheromone in the social behaviour of animals which can be observed from microscopic amoeba to insects and animals state by Arvin (Arvin et al., 2015). In their studies, they have found out that of different environmental factors such as the size and texture have the effects in the aggregation cues (BEECLUST, as shown in Figure 17) using real-robots. Additionally, a new mathematical model is presented to predict the behaviour of the aggregation during experiments.

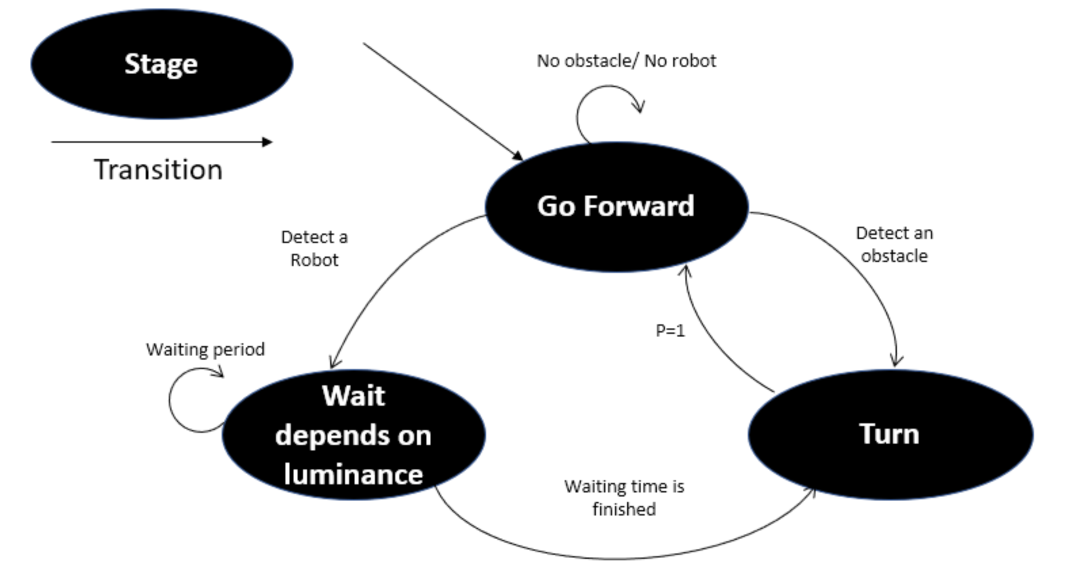


Figure 17: The finite state automation of the robots' behaviour in BEECLUST (adapted from Arvin et al., 2015).

In a group of living animals, aggregation favours interactions and information exchanges between individuals, and thus allows the emergence of complex collective behaviours (Figure 18) (Garnier et al., 2005). In this study, the implementation of a biological model of self-enhanced aggregation in a group of micro-robots is presented. Despite the limitation of different sensory abilities between biological and artificial models, the aggregation dynamics observed in robots closely matches those cockroaches in real-life scenarios. Moreover, the potential change of this aggregation model proves it can lead a group of robots to a collective ability to sense and compare the sizes of the aggregation sites.

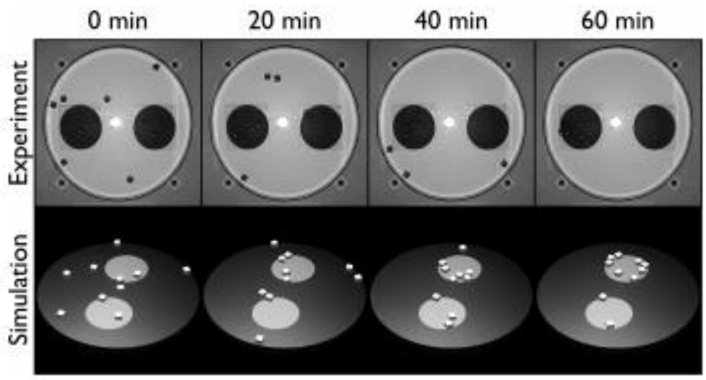


Figure 18: In this experiment, the robots' behaviours changes in every 20 mins, the two white circle simulate the shelters for the group-living robots (adapted from Garnier et al., 2005).

In 2003, a study by Trianni (Trianni et al., 2003) pointed out the possible evolving aggregation behaviours in a swarm of robots. In the study, they are using a simple robot, called s-bot, having the self-organised and self-assemble to form a robotic system called swarm-bot and having the ability to connect or disconnecting from each other. This physical link is used to self-assemble into a swarm-bot able to solve problems that cannot be solved by a singles-bot. The study also points out that the pheromone-based communication between robots can help the swarm robots have the aggregation ability to form together and finishing complex tasks. There are many studies about the self-organised aggregation in collective decision making in a group of micro-robots. The decision-making mechanisms are of crucial importance for any animal. They allow it to behave differently depends on different surrounding and situations. Garnier (Garnier et al., 2005) have presented the decision-making are highly influenced by the available spaces to explore and to aggregate in, the size of the population involved in the aggregation process and by the probability of exploring different zones within the same environment.

Inspired by the swarm intelligence observed in social insects, robotic swarms are fully distributed systems in which overall system tasks are typically achieved through self-organisation or emergence rather than direct control (Liu et al., 2007). In their research, they presented an adaptation mechanism which automatically adjusts the ratio of foragers and resters to maximise the net energy income to the swarm. Moreover, the mechanism can guide the swarm towards energy optimisation despite limited sensing and communication abilities between individual robots. From the results, it shows the swarm utilising social cues to achieve the highest net energy income to the swarm.

Foraging is a milestone problem in robotics, especially for distributed autonomous robotic systems. There are several reasons why the study of robot foraging is so essential. Firstly, because foraging is a metaphor for the broad class of problems integrating robotic exploration, navigation and object identification, manipulation and transport; secondly, in multi-robot systems foraging is a massive issue for the robot-robot cooperation; lastly, many of the real-world application for robotics are instances of foraging robots like cleaning, harvesting (Winfield, 2014). In this paper, Winfield has set up a theoretical framework that will be used in providing the basis of a principled approach to the engineering of future real-world robot foraging systems.

Furthermore, research that conducted to individual-based continuous time swarm and the motion is determined by three factors: 1) attraction to the other individuals on long distance; 2) repulsion from the other individuals on short distances; 3) attraction to the more favourable regions of the attractant/repellent profile. By following those factors, the results indicate there is a balance between interindividual interactions and the simultaneous interactions of the swarm members with their environment (Gazi and Passino, 2002). With a further study that published in 2004, Gazi (Gazi et al., 2004) have developed a simple model of swarming in the presence of an attractant/repellent or a nutrient profile and analyse its stability properties for different profiles. The model that they developed can be viewed as a representation of cohesive social foraging of swarms. This paper directly addresses the problem of coordination of agents and interactions with the environment based on simple potentials (Gazi et al., 2004).

In 2004, Liu (Liu et al., 2004) have presented a stable social foraging swarm in a noisy environment. They use a group of robots to simulate the coordinate their activities to search for and collect objects, to simulate the social foraging swarms. Noise is considerate from the sensor errors and errors in sensing the gradient of a “resource profile”. Result from the simulations illustrated advantages of social foraging in large groups relative to foraging alone since they show that a noisy resource profile can be more accurately tracked by a swarm than an individual (Liu et al., 2004).

Lerman and Galstyan (Lerman and Galstyan, 2002) presented a mathematical model of foraging in the size of robots and the performance agreement. The study found out with the larger group sizes, and the group performance declines due to the effects of interference. Also, from in-depth research in this area, increasing the robot group size reduce the total time needed for completing the tasks, in theory, the overall system performance is increased. However, this improvement is sub-linear, and the relative the foraging efficiency decreases as the size of the group grow due to the effects of interference.

In recent decades swarm intelligence (SI) has gained increasing attention as a bio-inspired approach to coordinating the behaviours of groups of simple robots in multi-robot systems (Liu and Winfield, 2010). New concepts of the sub-Probabilistic Finite State Machine (PFSM) and private/public time thresholds has been presented. The model has been validated extensively with simulation trials, and results show that the model achieves perfect accuracy in predicting the group performance of the swarm. Finally, a real-coded genetic algorithm is used to explore the parameter spaces and optimise the parameters of the adaptation algorithm.

2.2.2 Biological Background of Pheromone Communication and Artificial Pheromone System

There are a lot of different methods that are used by real-world animals to communicate and to transport information between each other. A possible solution was presented by Russell (Russell, 1999) in 1999 using ant trails for the other robot (as shown in Figures 19, 20 and 21) to follow in terms of gathering information and pathfinding. The paper indicates the potential power by using the ant trails following control algorithm to guide other robots in a complex environment has a massive impact on finishing the tasks more efficiently. Results of the experiments show the ants lay pheromone trails on the ground and transferring a patch of chemical signal. Those signals attract the followers to follow the information and navigating themselves to the destination.

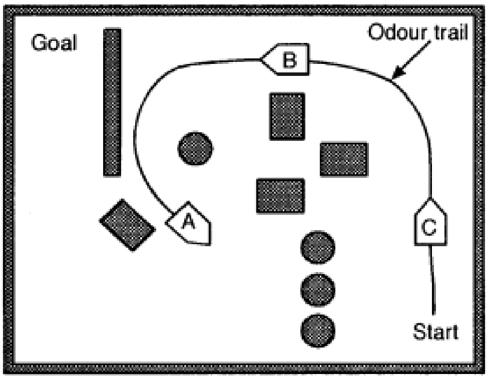


Figure 19: Laying down odour trails to guide outgoing or returning robots (adapted from Russell, 1999).

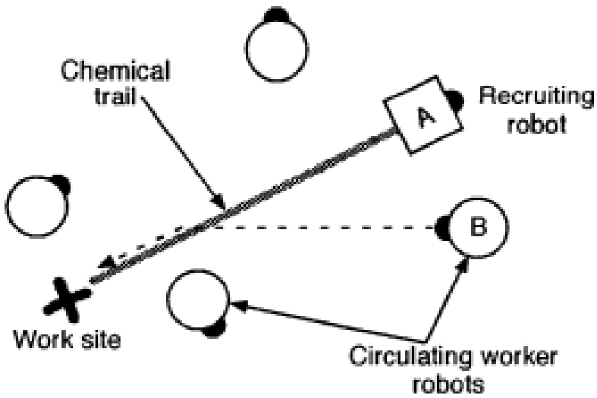


Figure 20: The circulating worker robots attracted by the chemical trails released by recruiting robot (adapted from Russell, 1999).

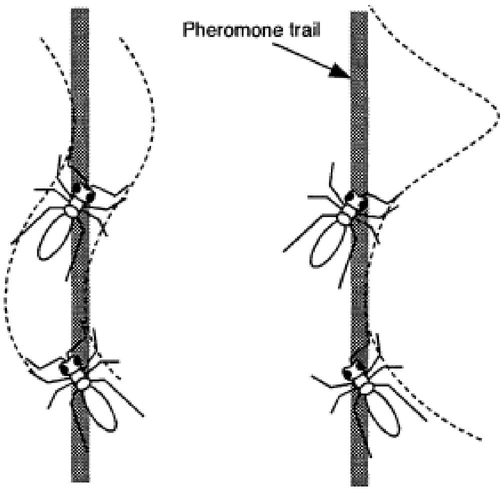


Figure 21: Trail following by the insect (adapted from Russell, 1999).

In 1978, threshold models of collective behaviour had presented by Granovetter (Granovetter, 1978), and this model is developed for situations like actors have two alternatives and the costs and/ or benefits of each depend on how many other actors choose which alternative. The critical point is the number of thresholds, or another one must decide before the given actor does so. The model of this paper treats binary decisions, and the outcome of choosing different choices will let to different results. The models are particularly valuable in helping to understand the situation where outcomes do not seem intuitively consistent with the underlying individual performances (Granovetter, 1978). This kind of model can be useful in small-group settings as well as those with a large number of actors; this is a tool for analysing the tasks that link to micro levels.

The cue-based and self-organised aggregation have been studied in swarm robotics for more than two decades. The studies on cue-based aggregation mainly focused on different methods of aggregation and different parameters such as the population size. In 2016, Arvin (Arvin et al., 2016) and his colleague had studied in the effects of different environmental factors; size, texture and number of cues in a static setting and moving cues in a dynamic setting using real robots. They used aggregation time and size of the aggregate as the two matrices to measure the performance. The results from the experiments show that environmental conditions affect aggregation performance considerably and have to be studied in depth (Arvin et al., 2016).

Although the insects have minimal communication method, they still can maintain the health of the colony, carrying for the young and responding to the invasions (Mohan and Ponnambalam, 2009). Pheromone communication is a two-component system: signalling pheromones and receiving sensory neurons. There are a few areas have been identified in the past according to Stowers and Marton (2005). Pheromones are unlike the familiar chemical odorants that generate biological signals to guide our behaviours.

There are a lot of different pheromone-based communications such as pathfinding in insects, food foraging and aggregations, and the use of insect's sex pheromone in the orchard pest management. A review in 2000 published by Suckling (Suckling, 2000), reviewed the recent progress of using the pheromone traps to lure insects in the orchard pest management. However, the paper highlighted the outstanding issues of the use of pheromone traps. The use of the pheromone trap has proved the potential power in direct control of orchard pest management. Also, he added, the job of using the pheromone to prevent the damage in orchard pest is far from complete, due to the identifying process of pests and beneficial insects. As importantly, the market for orchard produce is sending clear signals to growers and others that low-input and low-impact production system are required for the future development (Suckling, 2000). In 2008, a study of the pheromone disruption of Argentine ant trail integrity has conducted by Suckling (Suckling et al., 2008) In this study the Argentine ant uses the individual pheromone signal and combine the food pheromone signal to track down and passing the signal to other ants within the same area. This study uses several pheromones to disrupt the trace of food pheromone signal and the result is massive. Because of the Argentine ants are realise on the pheromone signal that produced by themselves and the food source. If there is a new trace of pheromone signal is released by the group member, it will change the course of the ants for finding correct paths (Suckling et al., 2008). This can be used as one of the ways to prevent insects damaging products in the field in the future. Because of the Argentine ant uses a trail of pheromone to formation and foraging, the potential work of using a new leader pheromone trail to disrupt the ongoing course is massive. Presented by Suckling (Suckling et al., 2010), the Argentine ant uses the pheromone trail to identify the food location and to communicate with each other using the pheromone trail. In the result, it shows by using the pheromone disruption significantly lower the number of ants on the card (which used to mean the ant is on the bait) and compare to non-pheromone disruption.

The use of pheromone communication not only can be used in orchard pest management in real-life but also can be used in swarm robotics to simulate real-life insects' interactions with each other. A 'virtual pheromone' was implemented by just using transceivers mounted atop each robot (Payton et al., 2001). Unlike the chemical markers used by the insect for communication and coordination, the virtual pheromone is symbolic messages tied to the robots themselves rather than to fixed locations in the environment. With the pheromone is tied to each robot in the arena, those robots can be track down each other very quickly and find the correct path for travelling.

A particular example of using the pheromone communication in guiding robots' behaviours was introduced in 2007 by Russell and Purnamadjaja (Russell and Purnamadjaja, 2007). This example take inspiration from the queen bee in a bee colony by keeping the colony stay together and stabilizing the colony. In the context of swarm robotics, the leader can release different type of signals to influence other robots' behaviours within the same group. In that paper, the pheromones were used to trigger congregating behaviour and light seeking in a group of robots. The results demonstrate the swarm robots can detect the pheromone chemicals released by the leader independently, the robots were able to execute the behaviours commanded by the robot leader (Russell and Purnamadjaja., 2007). A new version of bi-directional pheromone communication between robots was released by Russell and Purnamadjaja in 2010. There are a number of advantages for the use of pheromone communications in swarm robotics. The choice of different types of pheromones can guide the robots with different type of results, for example, the pheromone released by the leader is only used in the following leader scenario, the leader produces the trace of leader identification to help the followers identify and follow.

There are a lot of different method to simulate the pheromone for the robots to communicate with each other. A chemical substance for group foraging behaviour in swarm robotics pheromone communication was presented by Fujisawa et al. (Fujisawa et al., 2014). This approach is closer to the swarm robotic communication biologically which both use the signal of different pheromone traces. The experiment is set up with a fully autonomous robot and uses the pheromone trails to allow the robots to communicate with each other indirectly via pheromone trails. The idea of this experiment is to investigate any changes caused by the pheromone communication in the performance of the swarm in solving foraging and cooperative tasks. The result show that the robots can communicate using pheromone trails, and that the improvement due to pheromone communication may be non-linear, depending on the size of the robot swarm (Fujisawa et al., 2014).

Complex and adaptive population behaviour emerges in social insects. Ants particularly, by using the pheromone communication is the key to understanding their swarm intelligence (Kitamura et al., 2009). In their paper, they presented a swarm robot system based on pheromone communication to solve complex swarm robotics problems. In the previous researches, the pheromone is simulated by using the virtual pheromone (Payton et al., 2001), or later group that using the chemical substance (Fujisawa et al., 2014). In this research the virtual pheromones were replaced with graphics projected on the ground. The results demonstrate that by using the pheromone communication increase the efficiency of foraging compare to non-pheromone communication.

Foraging robots involved in a search and retrieval task may create paths to navigate faster in their environment (Dorigo et al., 2010). Under this context, the selection of which path is the main point of finding the fastest path to navigate through the process. In this paper, they implemented a virtual ant to lay artificial pheromone inside the network of robots, the messages are transmitted by robots locally. The results demonstrate the use of pheromone of path selection has effect to the efficiency of the interaction between the followers and the pheromone trace. The pheromone trace can potentially increase the performance and time efficiency of the robots to find the correct and fastest paths for travelling rather than going through a lot of times.

Pheromone-based communication is one of the most effective ways of communication widely observed in nature. It is used in insects socialising, mainly: ants, bees and termites. In this section, we will be looking at some of the applications that are used in modelling virtual pheromones and the localisation system that is used for the experiments in this thesis. The system is a pheromone-based communication experiment tool that developed explicitly for swarm robotics researches. This system uses one monitor to run the localisation system that locks on the robots, an LCD screen that is used to simulate pheromone trails in white light, and a low-cost USB camera that is above the second screen and connected to the first monitor for transferring data and record the experiments (Figure 22). The experiments are conducted using a group of Colias micro-robots (Arvin et al., 2015).

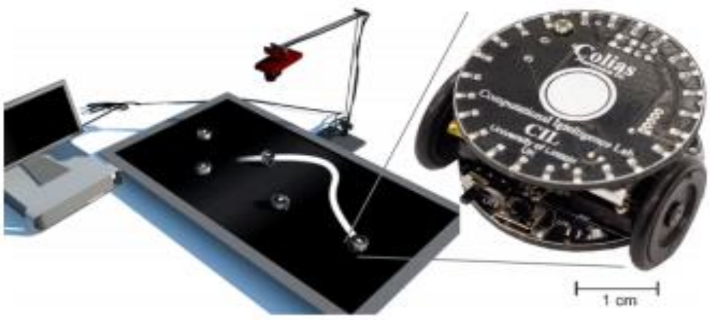


Figure 22: Artificial pheromone system with 5 Colias Robots.
(adapted from Arvin et al., 2015).

The system is separated into two main parts: the host monitoring that is running the multi-robot localisation method to quickly and precisely track down and lock down the robots in the arena. With off-the-shelf computational equipment and low-cost cameras, the core algorithm can process hundreds of images per second while tracking the robots' movement (Arvin et al., 2014). To be able to work as the system mean to be, the camera requires to locate the four different shapes of patterns and to use the patterns to find the correct area for the experiment (Figure 23). Although the system is fast and precise, their issues with the localisation system still exist. The time it takes to localising the arena takes time, and it highly depends on how large the LCD arena is, the bigger there are, the longer it takes. This is one of the primary functions that I used for my thesis, the localisation system monitoring and recording the experiment of each run, and it is the core of data analysis. Another one that of this kind of localisation system was presented by Krajník (Krajník et al., 2017). The algorithm gathering the statistical data of different types of circular pattern to search for the specific circular pattern. By using this method, the performance from the computational complexity perspective is significantly increased.

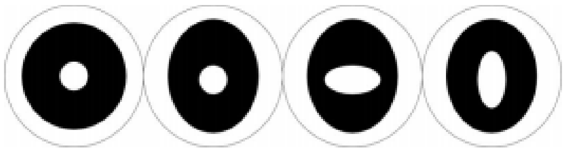


Figure 23: The first one is the original, the rest are modified localisation patterns (adapted from Arvin et al., 2014).

The other part is the vision-based pheromone system which is running on the LCD arena. The central core of this system is called the communication system via pheromone (COSΦ). The system is a high precision, flexible and low-cost experimental setup, which provides a reliable and user-friendly platform to study bio-inspired mechanisms (Krajník, 2014). The behaviour of the pheromone is determined into four parameters: injection, evaporation, diffusion and influence. Moreover, in my research, I have added the fifth parameter, the wind effects. This will increase the realism of the real-life environment scenarios of using pheromone-based communication.

Summary

A study of using digital pheromone for controlling and coordinating swarms of unmanned vehicles was published by Sauter (Sauter et al., 2005). The study demonstrates the effectiveness of these pheromone algorithms for surveillance, target acquisition, and tracking. In this study, a new way of displaying the pheromone has been introduced. The pheromone equation uses the two matrices to simulate the diffusion from point A to its neighbours. And the neighbour's diffusion will be sending some of the pheromone signal back to A. This function helps the researchers to simulate the pheromone diffusion in real-world scenarios, where the pheromone will not just be sending the pheromone trace into one place but also several places that surround itself. This function inspired me to upgrade the current algorithm that is used in the pheromone system in section 2.2.2. With the new algorithm, it can help me with more advanced pheromone system to simulate real-life scenarios even under different wind conditions.

Pheromone-based communication is a widely used communication method in insects and animals. A paper presented by Fujisawa (Fujisawa et al., 2008) demonstrate the potential power of using pheromone field to communicate in multiple robots. They construct a swarm behaviour simulator and develop swarm robots that communicate using the pheromone trail. They demonstrate the effectiveness of the communication using the pheromone trail by computer simulations and experiments using swarm robotics. The pheromone trail is simulating on a computational grid, and evaporation and diffusion are modelled by discretized equations. The experiment uses three robots, there are two stationary robots to simulate the nest and the target, and the last one is travelling from the nest to the target. The experiments take 20 mins and the robots laid down several trails of pheromone over the first-time travel. This result indicates the pheromone trail is the key point of the swarm robotics for pathfinding and the robots can follow the trace of the pheromone to find its target.

Chapter 3. Methodology

This section focuses on the current system for the artificial pheromone system which is based on the current pheromone model and algorithms. The artificial pheromone system will be presented in the following two parts: 1) the pheromone model and the wind model; 2) the localisation system.

3.1 The Pheromone Model and Wind Model

This sub-section introduces the pheromone models that are used in this thesis.

The first pheromone model is called the COSΦ (Communication System via Pheromone) and was presented by Arvin (Arvin et al., 2015). The COSΦ is a high precision, flexible and low-cost experimental setup that provides reliable and user-friendly platform to study bio-inspired mechanisms (Arvin et al., 2015). The system allows the leader micro-robot to simulate a trail of visual pheromone on the LCD screen and use several followers equipped with light sensors to detect and follow those trails. Moreover, the system also allows each robot to release several pheromones which depends on the user conditions. In this pheromone model they presented the behaviour of the pheromone is determined by four parameters:

1) Injection ι, which defines how fast a particular pheromone is released by a given robot.

2) Evaporation half-life e_{ϕ}, this determines how quickly the pheromone strength fades over time.

3) Diffusion κ, this defines the rate at which the pheromone is spreading.

4) Influence c, that defines how much pheromone influences the image displayed on the horizontal screen (Arvin et al., 2015).

The pheromone image displayed on the screen is presented as matrix I, brightness at the point (x, y) of the matrix presented as $I(x, y)$, and an i^{th} pheromone is modeled as a matrix Φ_i, the brightness of each pixel that is displayed on the horizontal screen is given by:

$$I(x,y) = \sum_{i=1}^{n} c_i \, \Phi_i \, (x,y) \tag{1}$$

$\Phi_i(x, y)$ is a 2D array that represents i^{th} pheromone intensity at location (x, y) and c_i defines the pheromone's influence on the displayed image. The value of c_i can be both positive and negative which allows the individual pheromones not only to increase the displayed pixel's brightness, but also to suppress it (Arvin et al., 2015).

The strength of each pheromone is continuously updated by:

$$\dot{\Phi}(x,y) = \frac{\ln 2}{e_{i\Phi}} \Phi_i(x,y) + \kappa_i \Delta\Phi_i(x,y) + \iota_i(x,y) \tag{2}$$

The $\dot{\Phi}_i(x, y)$ represents the rate of the pheromone change caused by the evaporation $e_{i\Phi}$, diffusion κ_i and injection ι_i. The injection $\iota_i(x, y)$ for a particular pheromone i and position (x, y) is determined by a set of conditions that are tied to the positions of the individual robots. Typically, a robot at a particular position would set the injection within a given radius to a particular value, i.e. (Arvin et al., 2015)

$$\iota_i(x,y) = \begin{cases} S_\Phi & \text{if} \sqrt{(x-x_r)^2 + (y-y_r)^2} \leq l_\Phi/2 \\ 0 & \text{otherwise,} \end{cases}, \tag{3}$$

(x_r, y_r) represent the position of the robot, l_Φ is the width of the pheromone trail and s_Φ is the pheromone release rate.

The system allows to extend the first term of the strength equation by a linear combination of all simulated pheromones:

$$\dot{\Phi}_i(x,y) = \sum e'_{ij\Phi}\, \Phi_j(x,y) + \kappa_i \Delta\Phi_i(x,y) + \iota_i(x,y). \tag{4}$$

The parameters $e'_{ij\Phi}$ defines how the strength of j^{th} pheromone affects the i^{th} pheromone rate of change, which corresponds to modelling the pheromone's interaction as a linear dynamical system. Since the pheromones released by different robots can have different conditions of evaporation and diffusion rates can strengthen or suppress each other, their interactions with the robots can result in a complex swarm behaviour.

This thesis mainly focus on only the leader agent can produce the pheromone trail for the followers to follow. Therefore, in this particular case only the diffusion and evaporation will influence the performance of the pheromone trail (without the wind effects). Although those two conditions could potentially strengthen or suppress the current intensity of the pheromone trail, the results should be not be influenced too much.

3.2 The Localisation System

This sub-section will focus on the localisation system model that is used in this thesis. In 2014, Krajník presented a practical multirotor localisation system. This core of this system is using algorithm to detect black and white patterns (Krajník et al., 2014). This system allows to track multiple patterns and calculates their 3D positions, but it does not distinguish between them and does not provide their orientations. However, evaluation of the swarm experiments requires to distinguish between the individual robots and to calculate their orientation (Arvin et al., 2015). Because of this issue, the new localisation model was introduced in the COSΦ (Communication System via Pheromone) by Arvin (Arvin et al., 2015). The localisation system is based on a freely available software package capable of fast and precise tracking of a large number of black-and-white patterns (Figure 24) that are placed on top of each robots. The core of this system is a method that can detect black and white roundel consisting of two concentric annuli with a white central disc. With the different shapes of the pattern, the robots can be signed with different IDs, this allows the user to identify each robot much easier and faster. Arvin and his colleague also implemented a self-calibration procedure that allows to automatically establish the relation between the image and real-world coordinates. The process usually takes less than 3 seconds depends on the size of the area and is automatically performed at the beginning of each experiment. This method decreases the chance of loss of localisation precision in case that the experiment preparation procedure accidentally affects the relative position of the localisation camera and the display. The self-calibration uses four circular patterns in known positions at each corner of the screen.

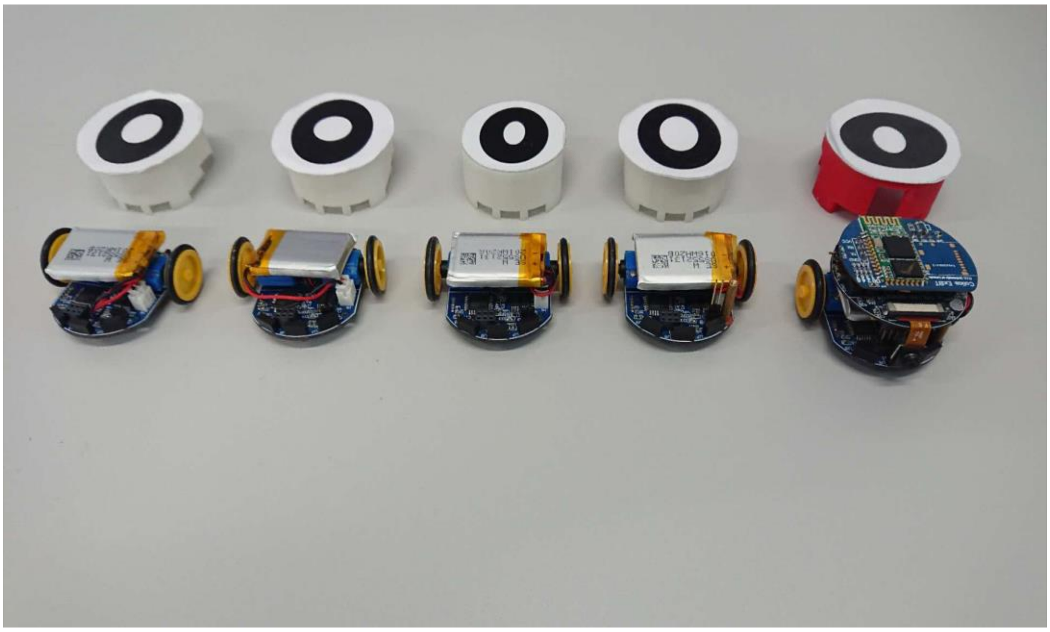


Figure 24: This image shows all the patterns that used in this thesis, the red one is the leader agents (But in the later experiment, the red case affects the performance of the leader robot's wheels so decided just to stick the patterns directly on the robot.), and the rest are the followers. The number of the leader is 1 and the rest is 2,3,4,5 respectively.

The current wind system is presented by Taylor (Taylor, 2018), in this system he proposed an idea to investigate the effects of wind to the pheromone trail that the leader produced in a following leader scenario. The model is based on Arvin's pheromone model (Arvin et al., 2015) and the localisation system updated with the wind effects to the pheromone trails released by the leader agent. In this model the visual effects of the wind affect (as shown in Fig.3.1) are linear which means the change of the pheromone is based on the movement of the pheromones are between each pixel. The model uses a simple algorithm that allows the pheromone to pass from the initial point to it neighbours:

$$K = i * width + j \tag{5}$$

K is the evaporation of the pheromone, i is the current row and j is the current column and the width is the total column in the displayed image. By using this method, it allows for adding to the current height or width to get the new location in the 2D array which means if adding 5 to the rows then it means 5 rows after the same columns.

By using this simple method allows to simulate a simple wind effects to the pheromone trails. The results show the robot perform better without the wind according to Taylor (Taylor, 2018). Despite the conclusion he made, the visual result from using this method (as Figure 25 shows), the trace of the pheromone is not accurate and if the wind condition is set too high, the trace of the pheromone will be showing on everywhere of the screen.

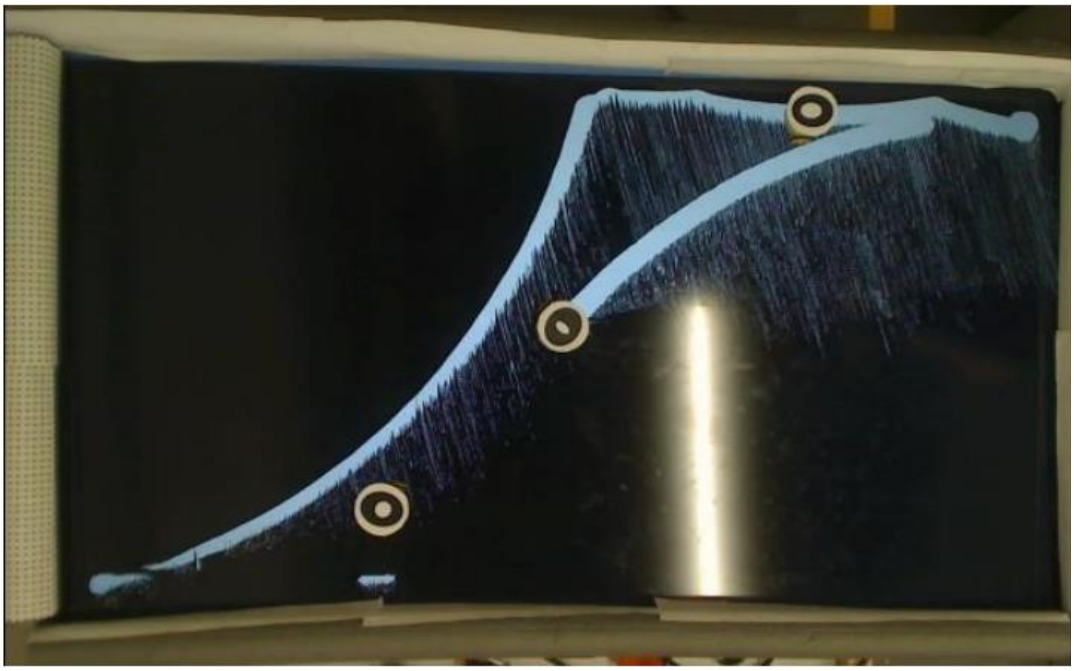


Figure 25: Taylor's wind effect model visual effect (adapted from Taylor, 2018).

In Taylor's wind model, he used algorithm to calculate the evaporation rate for the wind strength. The algorithm is taken from a published journal by Schouten (Schouten et al., 2011). The journal is about the wind speed and evaporation rates, and for Taylor's model he used part of the model and added with new method. The algorithm that Taylor took is:

$$E = \frac{(30.6 + 32.1 \times U)(P_W - P_A)}{\Delta H} \tag{6}$$

This model is used to calculate the inactive swimming pool water evaporation rate introduced by Smith (Smith et al., 1994). Where E is the evaporation rate, U is the wind speed, P_W is saturation vapor pressure at the water temperature, P_A is the saturation vapor pressure at the air dew point and ΔH is the latent heat of water at the pool temperature. Those two specific number is depending on different experiment settings.

Chapter 4. Implementation

This section will present the implementation of this research which includes 1) the robot behaviours; 2) the leader robot remote control; 3) the leader agent behaviours; 4) the pheromone communication system implementation; 4) the wind effects implementation and 5) data visualisation.

4.0 Robot Behaviour and Control in Arena Tests

This sub-section will focus on the robot behaviour designs in this thesis. In order to investigate the efficiency of wind effects to the food foraging using pheromone-based communication, the system requires to have the ability to separate two types of pheromone: the leader pheromone trail and the food area pheromone. And the experiments have divided into two different categories: 1) with/without leader interactions; 2) with/without wind interactions in leader interaction scenario.

The arena is separated into three different parts to simulate the food target area: top, mid and bottom. By making the food area located in different parts of the screen helps the variation of different food locations in real-life.

As shown in Figure 26, once the experiment has set up and start running. The robot will be running around the arena automatically, without the leader's pheromone trails, the micro-robots will only rely on their directions of movement and the adjustment when their close to obstacles towards the food area. Because of the sensors under the Colias Base Unit are programmed to detect the white light which means the system can detect different strength of light sources to determine the location where they are currently. This method allows once the micro-robot reaches the target area (simulated as a large white circle), the robot will send the stop command to the motors and stop moving inside the food area. Once the robot has reached the target area, a red light will

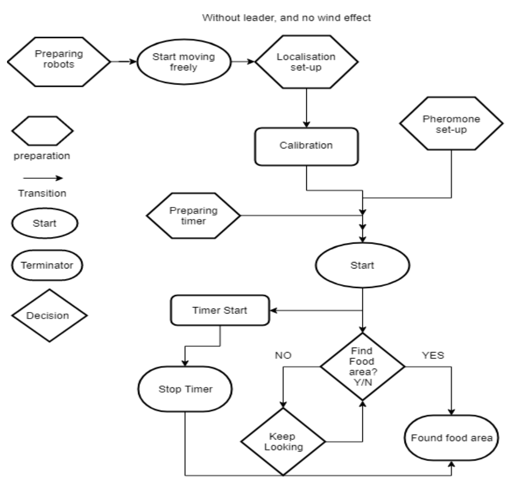


Figure 26: This is the process of the without wind and leader experiment. The experiment in this section is to investigate the basic time of completing the task without any interaction with the leader and wind effects.

light on and this means the robot is successfully completed the task.

The next experiment is added with leader interactions, the leader can release a trail of pheromone, this will allow other Colias to detect and follow the pheromone trails (Figure 27). In this set of experiments the leader knows where the target area is at and it is controlled by the user through the Colias Extension Unit. Therefore, the first hypothesis of this thesis is the leader knows where the food is, and the leader have the ability not just release the pheromone trails to help the followers, but also help other robots if they lost the directions. In theory, this method should potentially increase the performance of the micro-robot in food foraging scenario. Because of the leader is controllable and is straight to the food location.

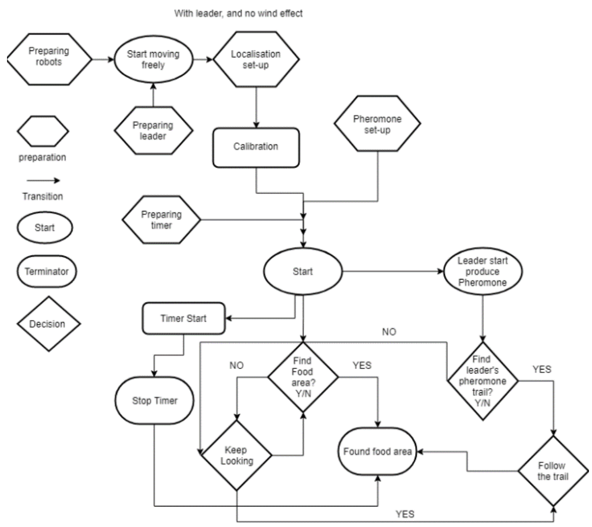


Figure 27 This figure presents the logical behind the leader interaction in the food foraging scenario. When the experiment starts, leader will start to produce pheromone traces, then the followers should be able to find those traces and follow it. But it is possible that the followers can’t find the leader’s pheromone trails, and it will keeps moving around and possibly find the leader’s traces or even reaches the food area without the leader’s help.

The wind effects to the pheromone is one of the interesting research areas. The potential wind could help the animals and insects to locate different types of pheromones and strengthen the pheromone intensity around one area. In this thesis, the wind effects will be investigating during the food foraging scenario with the leader interactions. However, the wind effects will only affect to the leader pheromone trails (Figure 28).

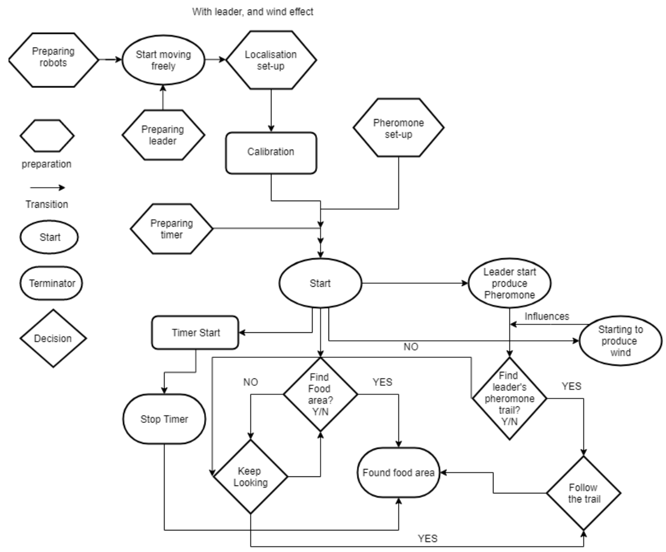


Figure 28: the wind effects to the food foraging scenario with the leader interactions. The wind effects are only affecting the leader pheromone trails. In theory, this could help the other micro-robots to locate the target area faster because of the travel of the pheromones.

4.1 Leader Robot User Control and Communication

This sub-section presents a method to control the leader agent in the food foraging scenario. The leader is equipped with the Colias Extension Unit as shown in Figure 29. In this unit, the main ability is the user can control the Colias using the Bluetooth through the serial port of host PC to control the Colias remotely. By using this method which increase the mobility of the leader agent and the ability of the leader in the food foraging scenarios. The controlling method is programmed in C# by using WinForms in Visual Studio 2017 Community (Figure 30). The user interface contains three main sections: the first section is used to establish the connection between the host and the Colias using the COM ports and the baud rate (a). But first, the Colias requires to open and need to connect to the host PC through the Bluetooth. Once the connection is completed then the rest of the user interface can start. The second section is a manual control panel (b), as the Colias can be controlled using command lines or using manual control, both of them processing the same dialog to make the Colias to react on different actions. The last section is the advanced command control panel (c), in this part user can use more specific command lines to control the micro-robot such as open camera etc. And one last section is the user interface can have certain dialog to help the user to see which lines that have been send to the Colias and executed (d).

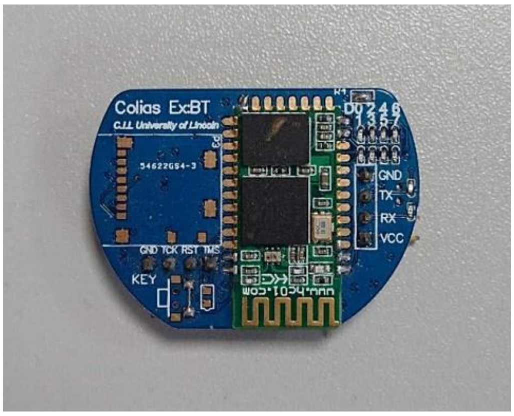


Figure 29: This is the image of the Colias Extension Unit used in this thesis, this is where the Bluetooth is embedded. The Bluetooth is used to receive the commands from the host and then passing down to the Colias Base Unit to execute.

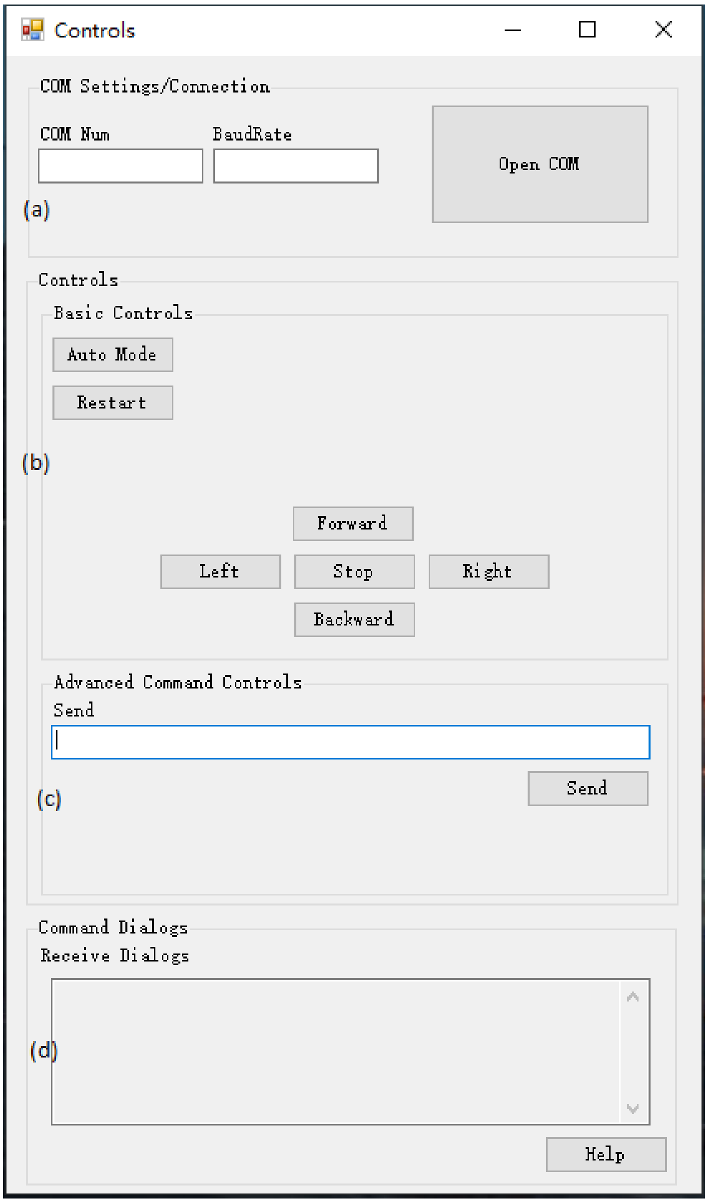


Figure 30: This is the leader control user interface in the host PC. This controls the leader's movement through out the experiment. And (a) is the COM port settings area which allow user to connect to the leader; (b) is the main control unit that allow user to manully controlling leader's movement; (c) will allow user to enter command lines to communicate with leader; (d) is the receive window to see if the robot has received the information that user sent to it.

The characteristic of the leader agent in this experiment is to help the other micro-robots to find the target area more efficiently. The first thing for the leader is to release the pheromone trails from the initial starting point to the target area which allows some of the micro-robots to detect the trails and follow them to the target. The second thing is if the other robot cannot locate the target area, the leader can move towards them and help them to get to the target area by host manual control as shown in Figure 31.

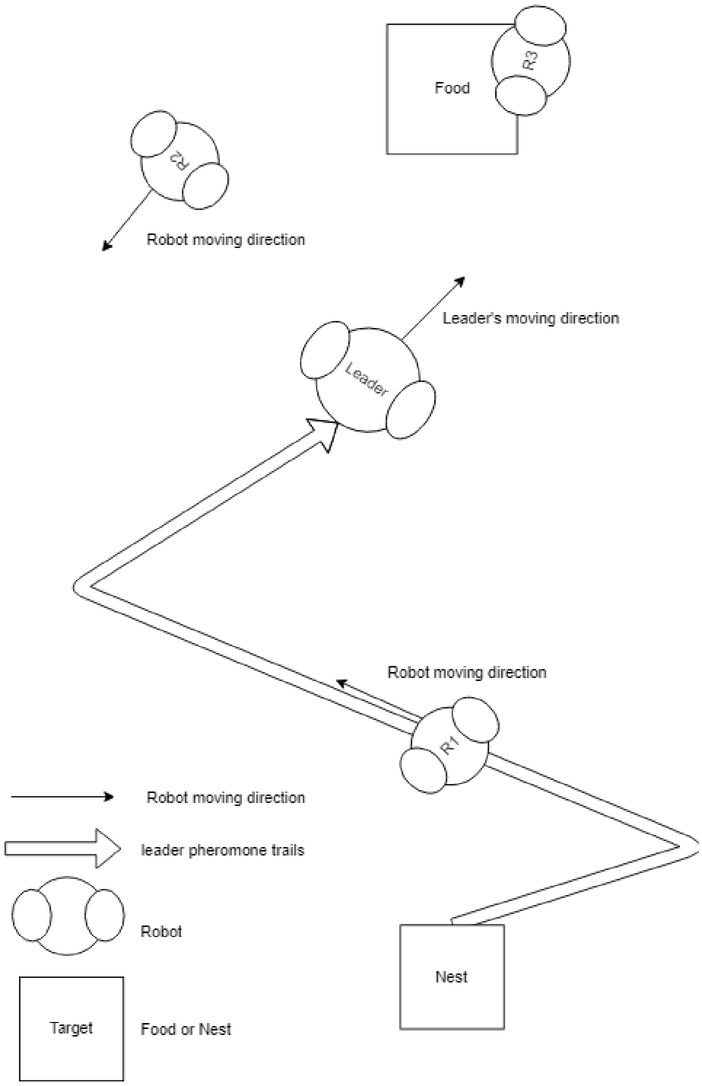


Figure 31: In this figure, the initial point is where the leader started. In the way to the target area, the leader releases the trail of pheromone and helped robot 1 to identify and follow to the target area. Robot 2 simulated the freely moving robot and find the target area. Robot 3 simulate those missing direction robots, once the leader reaches the target location, the first part of the job is finished. Then if there is any robot still not reach the location, the leader will go out the target area and help those robots back to the location area. This is the basic logic of the leader agent in this thesis, the same process applies with the wind effects as well.

4.2 Virtual Pheromone System Implementation

In this sub-section will demonstrate the virtual pheromone system that is implemented in this thesis. The current pheromone system is presented by Arvin (Arvin et al., 2015) and programmed in Linux Ubuntu with visual studio in C++. In this thesis, we present the current pheromone system with added new code to simulate the food area, and several attempts of making different style of food foraging.

Initially, in the food foraging the idea was to use the leader as the breaking point of this type of scenario. Because of the leader agent is controlled by the user using the Bluetooth, the idea was whenever the leader stops in the arena for more than 5 seconds, there will be a circle of high intensity of pheromone surrounding the leader. And by adding a stop threshold to the Colias Base Unit to make it has the ability to stop once it reaches the high intensity area. By using this method (as pseudocode shows in Appendix 1.) to start the food foraging scenario directly after the leader following scenario. The original idea to simulate the food area based on the leader's movements. However, this method was quickly turned down due to the position of the food area is always changing. Without the same location each time, the results are not stable and consistent. The location when the leader stops also affects the performance of the other micro-robots. Sometimes, the leader can stop right behind one of the other robots. Moreover, in some cases other robots can push away the leader and the timer are reset because of the position is changed by the followers.

In order to solve this issue, we decided to use the original idea was to simulate the location of the food area: by separating the second screen into 3 parts: top, middle and bottom. Moreover, in the original attempt the pheromone is shared by using the same pheromone strength settings from the original code. Other micro-robots cannot identify which is the area of the food and which one is the leader's pheromone trails. Therefore, in this thesis to separate the different pheromone released by the food and leader we need to separate them. (As pseudocode showed in Appendix 2.). This new method allows the leader to have additional ability to guide other micro-robots when they lost their direction and lead them towards the food area. The reason why I adjusted the value of the pheroStrength is because after several experiments, I found out the value controls the light brightness, and the influence controls the speed of refreshing the pheromone for each time. So, the greater the number the more sensitive of the light sensor embedded on the micro-robot and the difficult to separate the difference between the leader pheromone trails and the food pheromone strength.

After the adjustments on the pheromone system, we also need to adjust the Colias base unit program to suitable those new changes. The program is called the Ant pheromone and is programmed in C, to modify the code we need to use the CodeVisionAVR Evaluation to open the file, once inside the project we can modify the code as shown in Appendix 3. After adjusting the value of the Stop_Thr (the unit is the brightness), is time to use the Progisp connect the Colias using wires and re-write the data into the Colias. The number after the Stop_Thr is depends on three conditions: first, the light sources surrounding the arena. Both natural light source and human made light source can influence the result of experiment, because of the LCD screen's reflections from those light sources; second, is depends on the light sensors on each follower, some of the robots may have a larger number compare to others because of the design of each sensors; third, is depends on where the food area is located.

4.3 Wind Effect Generation

The current wind model is produced by Taylor (Taylor, 2018). That thesis investigated the effects to the efficiency of micro-robots in following leader scenario in swarm robotics. In this thesis, the wind model is used to investigate the following leader scenario with the food foraging. The wind effect is generated by using the following code (as Appendix 4 shows):
This is the modification in the CPheroField.cpp file, by adding the algorithm and a switch case for the experiment to run in different conditions. This method generates the wind effect by changing the evaporation rate to the pheromone trails that the leader agent released. And to make it works, it also requires adding more code in the main phero.cpp file (as Appendix 5 shows):

This is where the wind effect is added into the virtual pheromone system. Originally, I was planned to develop a new wind model to replace this one, but because of there is not enough time to let me do it, so the plan was cancelled. Therefore, we slightly changed the direction of investigation of the time efficiency in the leader following food foraging scenario. Instead of generating a realistic wind effect, we decided to change the conditions of the current wind model, for example, with three different wind strength we can have two different set of experiments with three small tasks individually. By changing the diffusion, the evaporation rate and the wind strength, we can have a solid idea of under what kind of situation the leader have the ability to help the other robots to finishing the task, and under which condition the efficiency is decreased and the leader’s effect is no more.

4.4 Data Visualisation

In this section, the data is from different type of experiments will be displayed into two different areas. The first area is about a table showing off all the time it takes to complete each task with different position of food area and the different number of robots. The time is recorded in t=0s and for each of the set of the experiments the number of robots is the same.

The first two sets of experiments used the same settings as follow: there are three different size of robots used to finish each set (1, 2, and 4 robots), to foraging at different positions of food area (top 1, middle 2 and bottom 3). Additionally, in the second set of experiment will added the leader interactions to the robots in each experiment. In the process of running each experiment the time is recorded as mentioned above, it is used to compare the difference and efficiency of using leader interactions and wind effects. Moreover, for each set of experiments run 20 times to show the difference of each time of running the experiments. To determines each task is completed by the robots successfully, the robots must stand within the area of the food, then the time stop record and the task is completed. The third set of experiment is different with the first two with wind effects on. Because of the experiment arena settings and natural light influences the set of experiment in this section is reduced only using 2 robots and the food area is in the middle.

4.4.1 The Trajectory of Follower agents in No-Leader and No-Wind Effects

Food Foraging scenario

In the following parts will demonstrate the different sets of experiments in this thesis, mainly separated into three parts: 1) without leader food foraging; 2) with leader interaction food foraging; 3) with leader interaction and the wind effects on leader's pheromone trails and food area.

Without the leader food foraging will be presented in three different size of the robots: 1 robot, 2 robots and 4 robots, and for each of them present a set of different locations of the food area in the order of: top, middle and bottom. Both the green and blue lines are the same as the trajectory of the robot. As Figure 32(a), (b) and (c) shows, the first set of experiment is to analyse the different time costs in different location of the food area and the different starting point with only one robot in the arena:

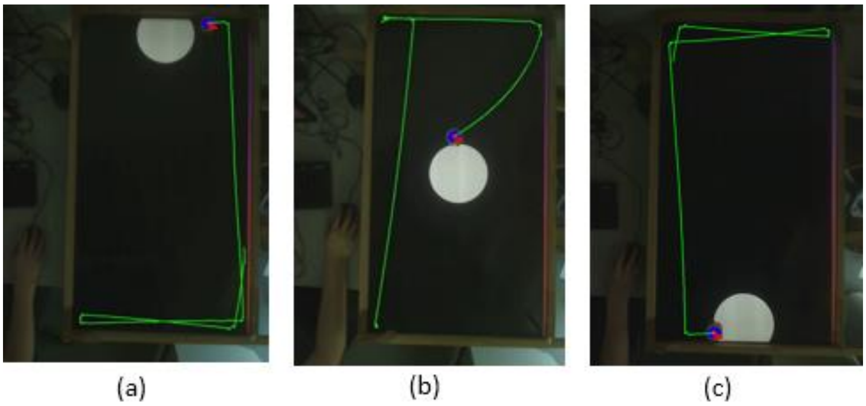


Figure 32: The trajectory of 1 robot where food location is at top of the screen (a), middle of the screen (b) and bottom of the screen (c) respectively.

The second category is the 2 robots' food foraging without the leader interaction as shown in Figure 33(a), (b) and (c):

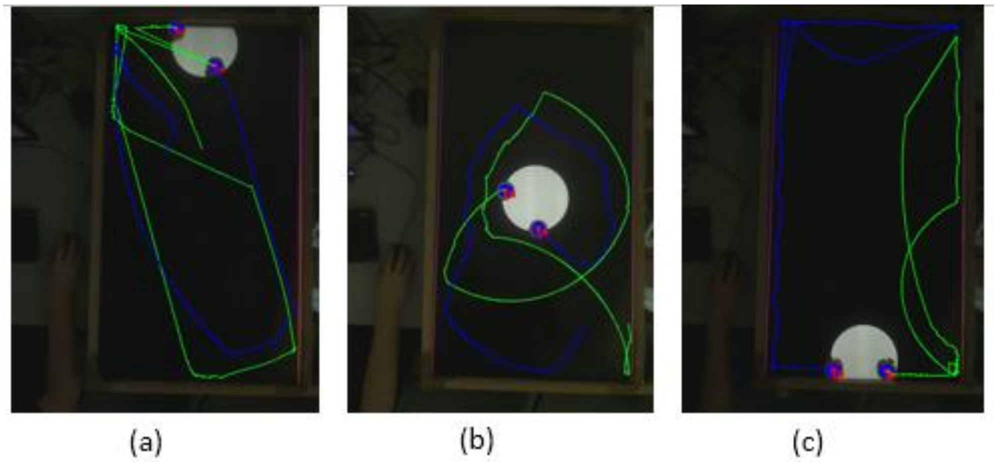


Figure 33: The trajectories of 2 robots where food location is at top of the screen (a), middle of the screen (b) and bottom of the screen (c) respectively.

The last one of the first set of the experiment is with four robots in the arena, this is the highest number that this system can support. If the number of robots is higher than four, it is very likely the robots will keeps affect to each other and decreasing the performance of the experiment and the food foraging time efficiency. The trajectory is showed in Figure 34 (a), (b) and (c).

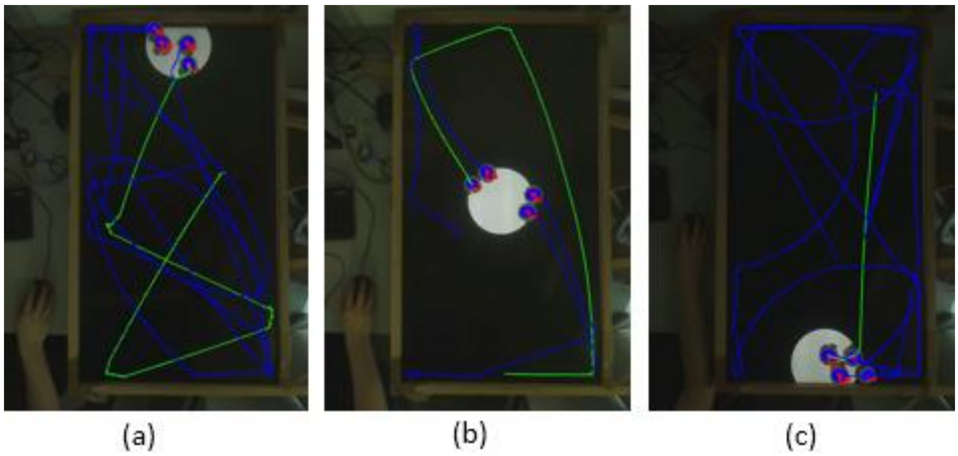


Figure 34: The trajectories of 4 robots where food location is at top of the screen (a), middle of the screen (b) and bottom of the screen (c) respectively.

Summary

The results and trajectory indicate even without the leader's pheromone trails, the micro-robot still has the ability to finish the task even with different group size and location of the food area. The starting position that presented in this section were all random to simulate the robots are freely moving before the start of each experiment and all the robots started moving at the same time when the experiment starts. However, without the leader interaction, the experiment usually takes more than 3 mins to complete and sometimes even more than 6 mins depends on which position of food area is. This part of the experiments is used as a background to compare with the next step with leader's pheromone interactions' time efficiency and performance. There are two factors affecting the performance and efficiency in the first set of experiments: the group size of the robot agents and the robot starting point and direction of they are facing when the experiment starts.

4.4.2 The Trajectory of Follower agents with Leader's pheromone interaction in Food Foraging scenario without wind effects

The second set of the experiments is with leader interaction. The leader's ability in this thesis is to help the other robots by releasing trails of pheromone. The strength of the leader pheromone and the food pheromone are different. Starting with only one robot and the leader agent in the arena, the trajectory as shown in Figure 35(a), (b) and (c). Note that the green line is represent the trajectory of the leader agent.

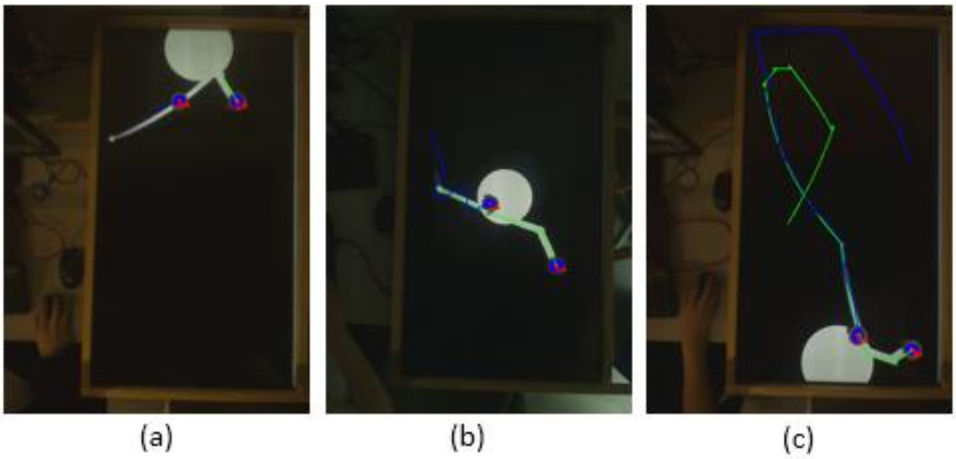


Figure 35: The trajectories of 2 followers with leader interactions where the food location is at top of the screen (a), middle of the screen (b) and bottom of the screen (c) respectively. In Figure 35 (a), both the leader and the followers were at the top area of the screen so the trajectory for both of them only has a little bit. As Figure 35 (b) and Figure 35 (c) show the trajectory of the followers once it detects the leader's pheromone trails then it will be starting to follow the trails of the pheromone.

The next part is two robots with leader in food foraging. The trajectory of the followers and the leader agent are shown in Figure 36 (a), (b) and (c).

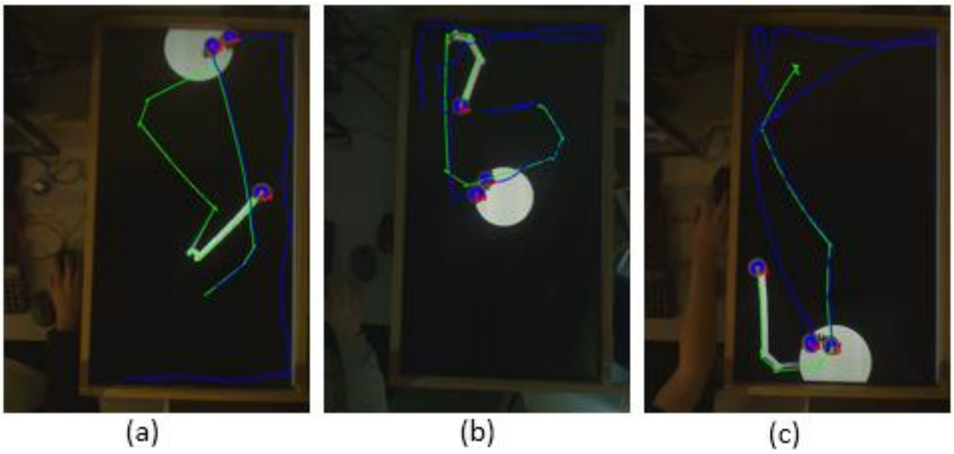


Figure 36: The trajectories of 2 followers with leader interactions where the food location is at top of the screen (a), middle of the screen (b) and bottom of the screen (c) respectively.

Summary

The potential of using the leader to guide the other robots in the arena is massive. Even with two robots in the arena, the leader still has the ability to help the get to the food area. But this method is not always the case, sometimes the robots have their own idea of moving to the food as shown in Figure 36 (a) and (c), one of the robots decided not following the leader towards the food area. This situation is happened due to the direction of other robots are random, the ability of the leader in helping the robots to find the food is limited.

The last is the four robots' food foraging with leader interaction, the trajectory as shown in Figure 37 (a), (b) and (c). In this set of the experiments, the issue of the robots finds the food area without leader interaction become common and, in some cases, some of the robots reach the food area even before the leader does due to the random initial position.

Figure 37: The trajectories of 4 followers with leader interactions where the food location is at top of the screen (a), middle of the screen (b) and bottom of the screen (c) respectively.

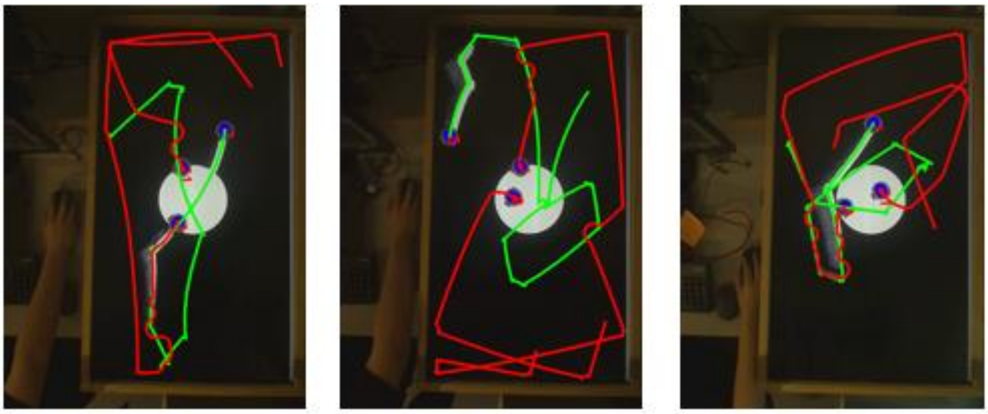
Summary

This is the end of the food foraging with the leader interaction. The trajectory shows the potential of using the leader agent in food foraging scenarios. Also, the trajectory reviews the robots can find the target area without the help of the leader pheromone trail. The results of these two sets of experiments also indicate interacting with the leader agent's pheromone trails can improve the performance in food foraging scenarios.

4.4.3 The Trajectory of using a leader's pheromone trails apply with the wind effects in food foraging with the follower robots.

The last part is about the food foraging with the leader interaction and the wind effect. The wind effects are separated into three different conditions in current wind model and the experiment will also focus on the influences of the changes of the diffusion rate and evaporation rate.

The first section of modifying different diffusion rate with the default wind strength as indicated in the code as case 1 (4 pixel/s from right to left). The diffusion rate is changing from 0.1 pixel per seconds (default diffusion rate used in this thesis) to 1.0 pixel per seconds that is the original number used in the current pheromone system. The trajectory of selected robots and the leader shown as follow Figure 38 (a), (b) and (c).



(a) (b) (c)

Figure 38: The trajectories of 2 followers with leader interactions and wind strength at case 1 (4 pixel/s) where the food location is at the middle of the screen. (a) is the default diffusion rate at 0.1 pixel/s; (b) is diffusion rate at 0.5 pixel/s; (c) is diffusion rate at 1.0 pixel/s.

In the current model, the wind effects are simulated by using the algorithm of the evaporation rate divided by the evaporation rate under different wind speed. Therefore, the change of the diffusion only has slight effects to the results of the experiment, the time it takes to complete for each experiment visually has slight changes. In the next section, the wind strength is changed from using the case 1 (4 pixel/s from right to left) to using the case 2 (8 pixel/s from right to left). As the wind speed is increased and the trajectory of using wind case 2 is showed from Figure 39 (a), (b) and (c).

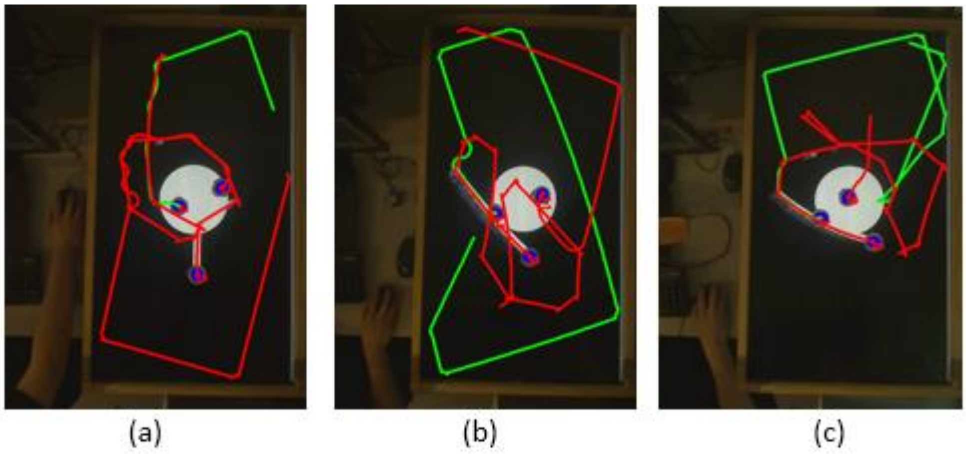


Figure 39: The trajectories of 2 followers with leader interactions and wind strength at 8 pixel/s (case 2) and diffusion rate for (a) is default, (b) is 0.5 pixel/s and (c) is 1.0 pixel/s.

Even with new wind strength and under different diffusion rate, the results and the efficiency of the follower robots' performance show no difference compare to wind strength case 1 (4 pixel/s). The following trajectory as shown in Figure 40 (a), (b) and (c) is under the diffusion rate of 1.0 pixel per seconds and the wind case 5 (24 pixel/s).

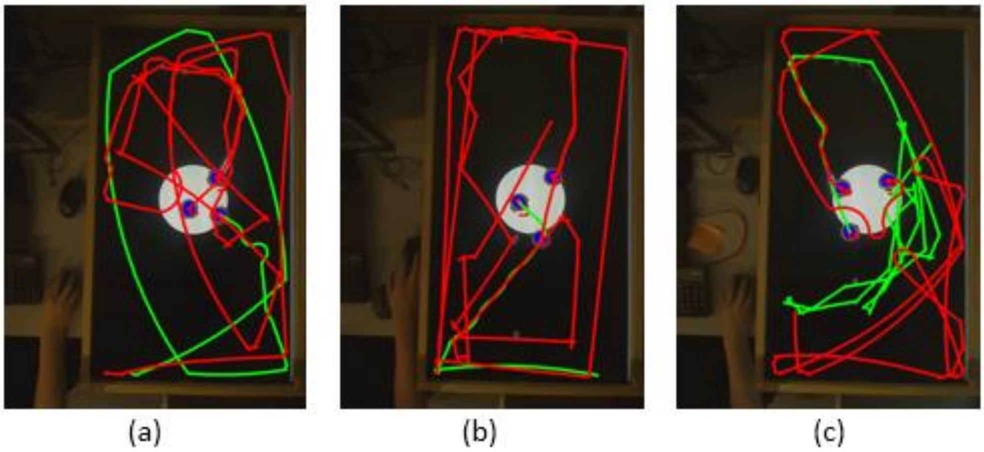


Figure 40: The trajectories of 2 followers with leader interactions and wind strength at 24 pixel/s (case 5) and diffusion rate for (a) is default, (b) is 0.5 pixel/s and (c) is 1.0 pixel/s.

Summary

In this first set of experiments, the result of the time efficiency shows no connection with the diffusion rate in current wind model. As the time efficiency in this part depending on where the robot is when the experiment starts. And the performance of the leader control, as in some cases, it is possible without the leader interactions, the follower agents has better performance, and even sometimes the robots can find the area without the leader pheromone trails as shown in Figure 38 (b) and Figure 40 (b) where the robot doesn't need leader's help. In Figure 40 (c), one of the agents changed the direction of moving because of the pheromone trails released by the leader.

4.4.4 The trajectory of leader and follower robots in food foraging scenario under different set of wind strength and evaporation rate.

The first experiment is by using the same wind strength case 1 (4 pixel/s) and modifying the different value of the evaporation rate from 0.6 pixel/s (the default rate used in most experiments), 0.8 pixel/s and 1.0 pixel/s to simulate different evaporation under the

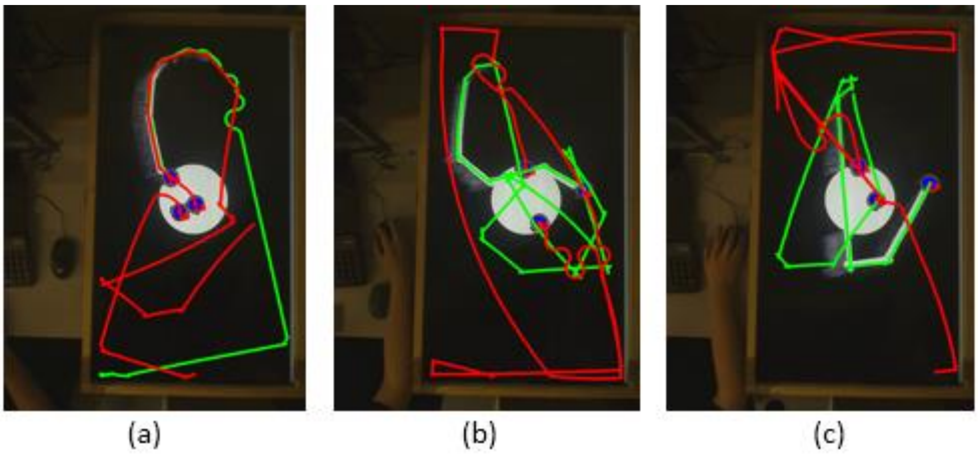


Figure 41: The trajectories of 2 followers with leader interactions at default diffusion rate, wind case 1 (4 pixel/s) and evaporation rate for (a) is 0.6 pixel/s, (b) is 0.8 pixel/s and (c) is 1.0 pixel/s

same wind case in Figure 41 (a), (b) and (c).

For the second category, it was decided not to use the 0.6 pixel/s evaporation rate as it is the default rate and has the same as result in section 4.4.3. Therefore, in the following 2 sections of the evaporation rate is from 0.8, 1.0 and 1.5 (Figure 42 (a), (b) and (c)) under the same wind strength case 2 (8 pixel/s).

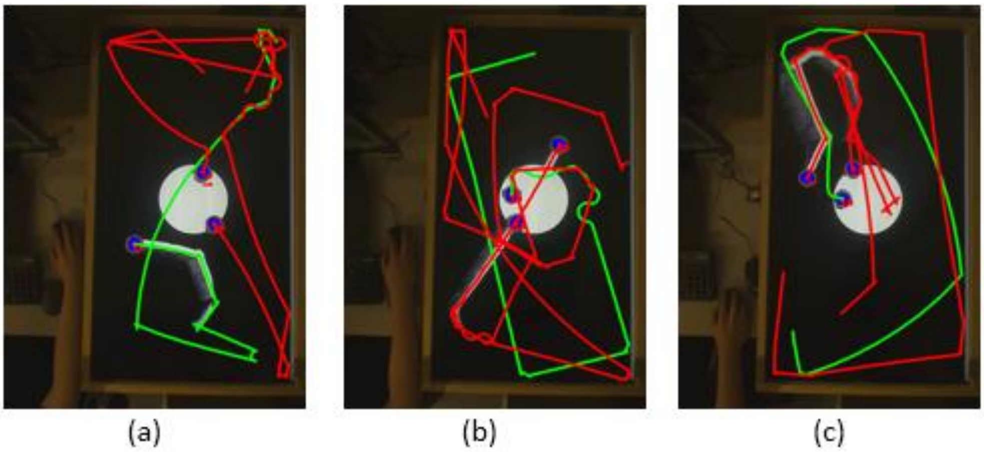


Figure 42: The trajectories of 2 followers with leader interactions at default diffusion rate, wind case 2 (8 pixel/s) and evaporation rate for (a) is 0.8 pixel/s, (b) is 1.0 pixel/s and (c) is 1.5 pixel/s.

The last part is with the wind strength case of 5 (24 pixel/s), and evaporation rate is 0.8 pixel/s, 1.0 pixel/s and 1.5 pixel/s as shown in Figure 43 (a), (b) and (c).

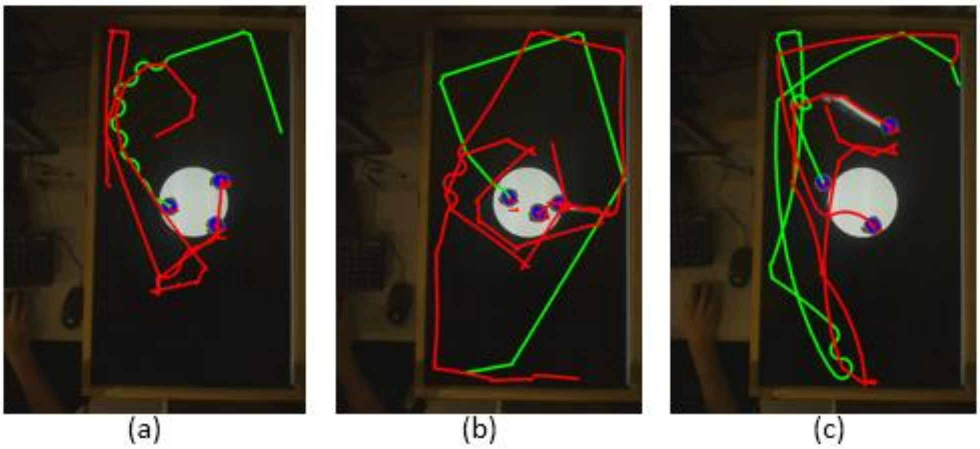


Figure 43: The trajectories of 2 followers with leader interactions at default diffusion rate, wind case 5 (24 pixel/s) and evaporation rate for (a) is 0.8 pixel/s, (b) is 1.0 pixel/s and (c) is 1.5 pixel/s.

Summary

In this part of experiments, the trajectory shows the evaporation rate the wind strength are the main conditions of influencing the wind strength in current wind model. With the evaporation rate set to the same number as the default rate presented by Arvin (Arvin et al., 2015), the leader started to have a hard time in guide the other robots, as the pheromone trails started to fade extremely fast and there is not enough information for the follower agents detect and follow. Only in some cases that the follower agents are close by the leader when the experiment starts and manually control the leader to engage the follower agents directly.

Chapter 5. Experimental Evaluation

This section presents three main sections: 1.the experimental settings for different type of experiments; 2. the results of using the leader agent in food foraging scenario: 1) investigation of food foraging efficiency without wind effects; 2) investigation of wind influences on leader following efficiency. 3. The discussion about the results of the experiments.

5.1 Experimental Setting

This section will demonstrate the experimental settings in this thesis: 1) software and hardware configuration; 2) the TV arena settings.

5.1.1 Software and Hardware Configuration

This subsection will present the configuration of experimental settings. The user interface for the leader control is programmed in Visual Studio 2017 Community using C# WinForms. The leader is controlled through the Bluetooth between the host and the serial port embedded on the Colias Extension Unit. The first thing to do is to set-up the connection between the host PC and the Colias. By opening the host PC's Bluetooth and the Colias should be able to add new device. The next step is to set-up the COM number of the leader control user interface (as shown in Figure 30(a)). The COM number is depending on the host PC, in my case it is COM4 or COM3 and the baud rate is 115200 bit/s. Once entered everything in the space press Open COM and should be able to receive a dialog in the receive dialogs area as shown in Figure 30(d). The other micro-robots run automatically after turning on the power. The robot can be controlled manually or using the command lines as shown in Figure 30(b) and Figure 30(c).

5.1.2 Experimental Set-up

There are two main functions in this part. The first one is the localisation system and the second is the pheromone system. If the experiment is running in a dual monitor, the pheromone system requires to be displayed in the separate monitor to be able to run. Additionally, in the dual monitors' situation, a top-down camera setting is required for recording the images for the localisation system (as shown in Figure 44).

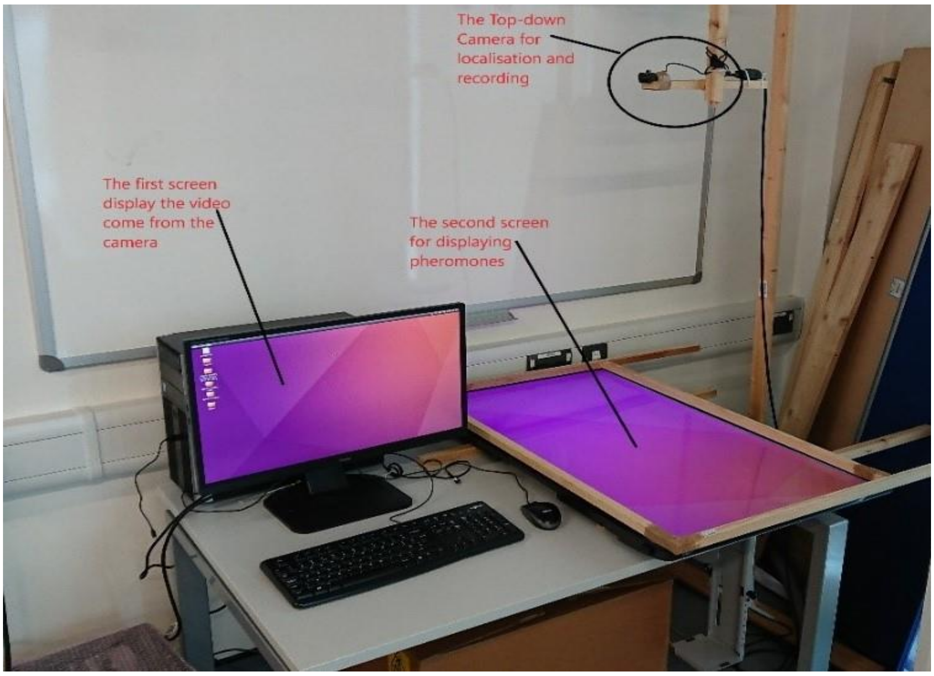


Figure 44: The TV arena.

The localisation system requires to be opened in Linux; the route of the opening depends on where it stored. In this thesis, the location of the localisation system is:

/Desktop/CosPhi-master_Leader_Follow_Food_Foraging/Localization/bin$.

Depends on how many robots are used in the experiment, in this case is two robots, therefore, the line will be: *./swarmcon /dev/video0 2* (as Figure 55 shows).

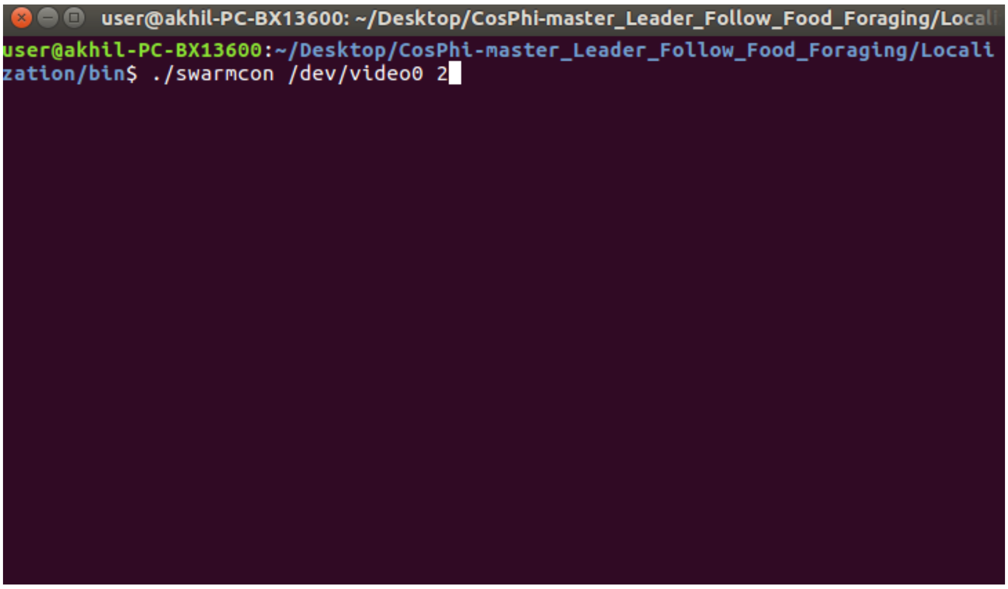


Figure 55: The localisation system in the experiment of 2 robots food foraging.

After that is the pheromone system, the route for the pheromone system is */Desktop/CosPhi-master_Leader_Follow_Food_Foraging/Pheromone/bin$.* And this should be put into the second screen if using the dual monitors. The settings in this example is: *./phero 0.5 2 0 3 180*. The first number is the diffusion rate, the second number represent how many robots in the arena, the third number is the wind effect, forth number is where the target area is located (1 is at the top, 2 is at the middle and 3 is at the bottom of the screen) and the last number is the size of the target area. In this example, the settings mean: there are two robots in the arena will moving towards location 3 under no wind effects and the diffusion rate of the pheromone is 0.5 pixel/s.

5.2 Investigation of Food Foraging Efficiency without Wind Effect

This subsection will demonstrate the investigation of food foraging efficiency without the wind effects. The experiment is separate into two different sets: 1) without the leader interactions; 2) with the leader pheromone interactions and the leader has the ability to

(Figure 56) (Figure 57) (Figure 58)

Figure 56: The Foraging time vs the Number of Testing Robot Agents in the Arena, where the food position is at the top.
Figure 57: The Foraging time vs the Number of Testing Robot Agents in the Arena, where the food position is at the middle.
Figure 58: The Foraging time vs the Number of Testing Robot Agents in the Arena, where the food position is at the bottom.

help the other robots to find the target.

5.2.1 Foraging results without a Leader Agent / With Leader Agent

The results indicate even without the leader agent interaction (as shown in Figure 56, 57 and 58 in red line), the micro-robot have the ability to find the target area moving freely. But the time efficiency is highly depending on the position of the micro-robot. Sometimes the robot is close to the target area when the experiment starts, then the time it takes to complete is very low. Moreover, the design of the micro-robot's motor and wheels are also one of the factors influencing the performance of the micro-robot. In the design of the micro-robot, there is an issue with the left wheel is slightly faster than the right wheel. Because of this design problem, the robot is very difficult to maintain a straight line when moving around the arena. In 1 robot scenario, the time it takes to complete the task is very low because of there is not too many interactions between robots and the environment, most of the time the robot can finish the task within 1 min. On the other hand, the 2 robots experiment performance is average due to sometimes the robots could trap them with each other and requires for human interaction to solve the problem. And the 4 robots experiment performance is the worst without the leader interactions with the robot. The problem can be summarised into two parts: 1) the robot is trapped in those four arena corners; 2) the robots are overcrowded. In conclusion, food foraging without the leader interaction and wind influence, the performance is highly depending on the position of the robot, the direction of the robot is moving when the experiment starts and the light source in the time of experiment is conducted.

And without leader interactions in the pheromone-based communication in food foraging scenario (Figure 56 57 and 58 in blue line). The use of the leader agent is to increase the performance and increase the efficiency of food foraging in theory. The results indicate the potential of using the leader to interact with other micro-robots is one of the methods to increasing the performance and compare to the without leader scenario, the time it takes to complete one task is decreased rapidly in some situations. For example, in the without leader agent interactions, the micro-robots usually take more than 1 min to finish the task, but with the leader the time can be taken under 50 s to complete the same task with the same settings. In this research, the leader 'knows' where he is going, and it has the job to guide the other robots to find the target food. Therefore, because of the leader is controllable, in some situations, the time it takes is hugely decreased. And with the help of the leader agent, other robots can locate where the leader pheromone is and follow it. However, because of the pheromone is simulated in another screen, the surrounding environment is one of the factors that influence the experiment. Especially, if the outside light is higher than inside the experiment can be unstable due to the difference of the light in the surrounding, and the light sensors embedded on the Colias Base Unit is very sensitive to those changes of surrounding light, the results can be unstable. In conclusion, that the leader does have the power to help the other robots find the target, and at the same time the leader's pheromone can disrupt the path of the robot. In some particular situations where the micro-robots detect the pheromone light and go to the opposite route of the leader or the leader could be run into the other robot and push them out of the correct route. Despite the issues, the results show the leader can affect other micro-robot's food foraging time efficiency, both in increasing the performance and decrease the time used and increase the time used and decrease the performance.

5.3 Investigation of Wind Influences on Leader Following Efficiency

In this section will demonstrate the wind influences on the leader following efficiency. After further investigation, for the experiments on the wind influences on the leader following efficiency will only focus on two robots and a leader agent and the food area will be in the middle. Because of the natural light is one of the factors that influences the experiments in this thesis. Both position 1 and 3 have huge differences compare to the position 2. Therefore, with limited time, we decided to use the position 2 (middle) and two robots with the leader agent to test the influences of using the wind in following leader and food foraging efficiency.

5.3.1 Testing on the changes of diffusion rate under different wind speed

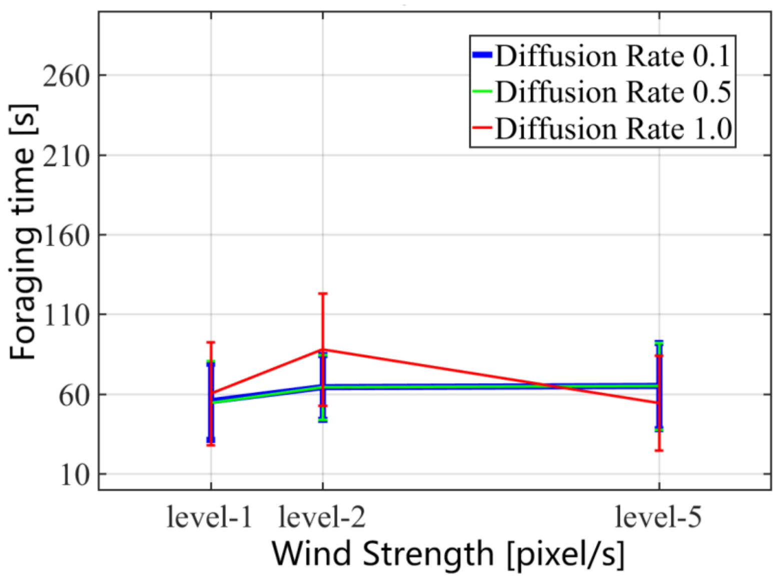


Figure 59: The Foraging time vs the Wind Strength in the Arena, where the food position is at the bottom; wind strength is pixel/s, level 1 is at 4 pixel/s, 2 is at 8 pixel/s, and 5 is 24 pixel/s; the diffusion rate unit is also pixel/s.

After experimenting different rates of the diffusion (Figure 59), the results indicate in the current model the diffusion rate does not affect too much of the efficiency of the leader following and food foraging scenarios. Particularly, the different rate of the diffusion under different set of the wind speed, the changes of the pheromone trails are limited or in another way is not affected. This thesis tested different rate of the diffusion even reaches 1.0 pixel/s as the default used in this thesis is only 0.1 pixel/s. The changes only have slight effect to the pheromone trails. As the result shows in the Figure 59, the diffusion rate 0.1 pixel/s and the diffusion rate 1.0 pixel/s has very slight difference between them, the time efficiency only changes rapidly with the diffusion rate of 0.5 pixel/s but still none of the result indicates the diffusion rate affects the data more than the evaporation rate in this current model. Moreover, both followers still be able to detect and follow the leader's pheromone trails. The possible issue of this result could be the current wind algorithm that only takes the evaporation and the wind speed as the main parts in the wind effects of the pheromone-based communication.

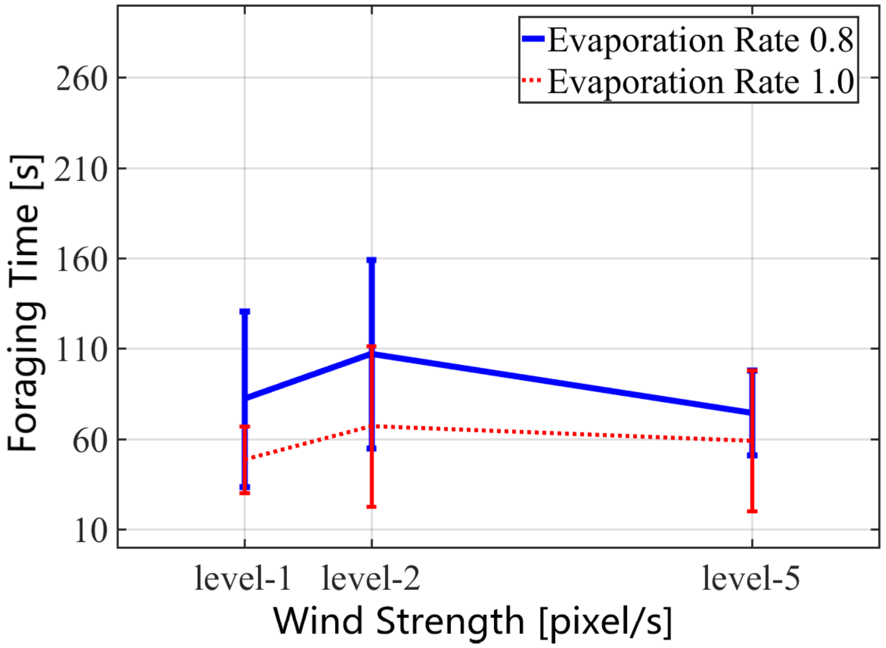


Figure 60: The Foraging time in seconds vs the different wind strength and under different evaporation rate; wind strength is pixel/s, level 1 is at 4 pixel/s, 2 is at 8 pixel/s, and 5 is 24 pixel/s; the evaporation rate unit is also pixel/s.

5.3.2 Testing on the changes of evaporation rate under different wind speed

The results (Figure 60) from the experiments indicate by changing the evaporation rate and the wind speed can affect the performance of the leader agent. With the evaporation rate adjusted to 1.5 pixel/s and with wind strength of case 5 (24 pixel/s), the leader has a hard time to guide the other robots. Because of under those conditions, the pheromone trails cannot stay long enough, and the length of the pheromone trials is too short. Both the length and the duration of the pheromone trails are the core of the current wind effect model. In some cases, that the robots perform better without interacting with the leader pheromone trails. And it is also possible in some cases that the leader's pheromone trails can provide wrong information for the followers to follow and change the direction of the route.

In conclusion, in the current wind effect model, the evaporation rate and the speed of the wind are the main factors of affecting the leader's pheromone trails' performance. Both of them controls the length and the duration of the pheromone trails that are released by the leader in the arena. For example, the first set of investigation of changing the rate of the diffusion, the pheromone that released by the leader still have the potential power to guide the other robots in finding the food area. However, with a slight change of the evaporation under the same wind strength, the leader has lost its ability to help the others, even became the 'bad' guidance that lead the robots to the wrong direction.

Summary

The use of the pheromone-based communication is one of the communication methods that is used in animals and insects. Based on this communication and inspired from it, this thesis presented an investigation of using pheromone-based communication to improve the time efficiency and the performance in food foraging and aggregation in swarm robotics. The results indicate the potential of using the pheromone to help the other micro-robots in the food foraging scenarios. Particularly in Figure 57, the investigation of experimenting the food foraging with or without the leader in food foraging proves the leader can play a significant role to help the other followers to reach a certain food source more efficiently. Despite the pheromone can sometimes lead the followers into the opposite route but in most of the cases, the time it takes to complete the task is hugely decreased.

However, the results also identified some issues with the current model of the pheromone system and the Colias micro-robot platform. The performance of the robot to complete the task is highly depends on the surrounding environment. Because of the current design of the Colias micro-robot platform uses two light sensors at the bottom of the Colias Base Unit. The light sensors are very sensitive to its surrounding light sources. The changes of the basis program of the Colias Base Unit can only temporarily fixed nature light issue, but if the outside light changes the experiment result will be influenced. The design of the Colias micro-robot platform made it smaller but in some cases the design of the wheels can lead to the worst scenario where two robots trapped together because of the wheel design and requires human interaction to help them to fix the problem. And the size of the arena and the size of the micro-robot also one of the factors of success and failure. The size of current arena is too small to carry out a larger size experiment and because of the design of the current Colias micro-robot platform also makes the size of the robot cannot be too large. Another issue is where the TV arena setup, some of the places are extremely depends on the surrounding environment, for example, the light source at the food position 1 is lower than the other two positions. In this position, it is very hard to do experiments due to the current design of the light sensors requires a suitable natural light source to have a better performance. The corners are also the problem of decreasing the performance and time efficiency, in the current model the robots can detect any incoming objects and using the bumpers to avoid those targets, but this method doesn't work in the corner area, and it is very hard to setup any blocks to help the robots because of the block could also affect the performance of the localisation system.

To be able to control the leader is one of the points that presented in this thesis. But there are a few problems with controlling the leader in the following leader and food foraging scenarios. Such as, the followers don't use other sensors except the bumpers in the front of the robot. And the bumpers only work when incoming object isn't moving, so in this case, that the followers could trap themselves behind the leader, and because of the program of the micro-robots to adjust the position to avoid the object. This could also trap the leader and requires stopping the leader or even human interacting the experiment. Therefore, the use of the controllable leader to guide the other robots is a good idea but lack of experiences in real experiments.

Therefore, some of the experiments on the wind effects or the leader following scenario can only be narrow down into two sections. Initially, in this thesis will be presenting a new wind model, without enough time and the new wind model is cancelled. The challenge of this research is not because of the skills needed to complete but mostly is the insufficient time to prepare it. In this research, a new wind model was initially designed to present. However, with the limited time and poor planning. So, instead of making the new wind model, by modifying different wind speed condition and the pheromone conditions to make the current wind model more realistic. And maybe in the future with better Colias micro-robot platform design the wind model and the new pheromone system can be implemented. But without enough time and better experiment environment it is very hard for me to complete this task. Despite this change, the results of this thesis are pretty good and the potential of using a controllable leader agent to interact with the followers in the leader following and food foraging scenario have the ability to increase the performance and efficiency compare to without leader effects.

Chapter 6. Conclusion

In this thesis, an investigation on the time efficiency by using the leader agents and wind effect in the food foraging, leader following in a certain food source area is presented. The investigation shows the potential of using the leader interactions in the food foraging and leader following scenario is a great idea for the swarm robotics' researches. The leader in this thesis is controlled by the host via Bluetooth, this method granted the leader with ability to guide the other robots in the food foraging scenario. Moreover, because of the leader is controllable, therefore in some cases the efficiency compares to the previous design, the time it takes to complete the task is decreased, and the time efficiency is increased and as well as the performance.

The systematic and comparative experiments demonstrate the importance of a leader in shaping pheromone-based swarm behaviours. Importantly, even influenced by the wind effects, the leader can well guide the other ordinary agents to finish the food foraging tasks, in most cases. For example, by adding a visual module to the micro-robot system can increase the performance of the followers to following the leader or helping the leader to find the target in the arena. It will also increase the chance of following the right trails that the leader is produced not just with the algorithm that triggered by white light in all sensors, but also with the vision that it can help the followers lack on to the leader.

The simulation result can be better, if the arena is larger than the current one, it will increase the number of robots and eventually increase the performance of each experiment and decrease the errors. It is also possible that we can add the obstacles avoiding ability to the micro-robots. The issue that the current version has is the followers often run into one or others, and ultimately decrease the performance of each run. With the obstacles avoiding technique and the vision system will hugely decrease the chance of errors and increase the performance and efficiency of each run.

Appendix

```
//To update the location of the leader every 5 seonds, we need to initialise the conditions.
float leader_X_old = 0.0;
folat leader_Y_old = 0.0;

//The pherofield 3 allows the leader to release a circle of pheromone once it stops for more than 5 seconds in one area
pherofield[3] = new CPheroField(imageWidth,imageHeight,0,0,2,pheroScale,pheroStrength);

//We need to create a timer for the leader
CTimer leaderTimer;
float leader_time = 0.0;
leaderTimer.start();
//The Flag indicating if the leader stopped
char StopFlag = 0;

//After the Pheromone injection, the leader timer starts
leaderTimer.start();

//Pheromone 4 used to check if the leader has stopped for 5 seconds
leader_time = leaderTimer.getTime()/1000000;

if(leader_time >= 5){
    printf("reset leader timer at %f\n", leader_time);
    float dis = pow(client->getX(leader)*imageWidth/arenaLength-leader_X_old,2) + pow(client->getY(leader)*imageHeight/arenaWidth-leader_Y_old,2);
    //Becaues of the system may have errors in position, therefore by adjusting the threshold could increase performance
    if(dis < 10){
        //set the stop flag
        StopFlag = 1;
        leaderTiemr.pause();
    }
    else{
        //This is used for if the leader doesn't stop, then update the new position and reset the timer
        leader_X_old = client ->getX(leader)*imageWidth/arenaLength;
        leader_Y_old = client->getY(leader)*imageHeight/arenaWidth;
        StopFlag = 0;
        leaderTimer.reset();
    }
}

//Checking the timer
leader_time = leaderTimer.getTime()/1000000.0;
printf("leader time now == %.5f\n", leader_time);
if(leader_time >= 5.0){
    printf("reset at time = %5f\n", leader_time);
    leaderTimer.reset();
}

//After the leader is stopped, the pheromone is a circle around the leader, therefore we need to have a radius, here is 200
if(StopFlag){
    int leaderID = 1;
    pherofield[3]->addTo(client->getX(leaderID)*imageWidth/arenaLength,client->getY(leaderID)*imageHeight/arenaWidth,leaderID,pheroStrength,200);
}

//In the original code, the value of phero in total was 3, but with the new added phero circle for the leader we need to change it to 4
image -> combinePheromones(pherofield,4,0);
```

Appendix 1: The original idea of making the food foraging area and robots stopping method.

```
// This is the new method that used in this thesis.
// To seperate the pheromone from the leader and the food area, I added a new pheromone strength

float pheroStrength = 5.5;
float pheroFoodStrength = 255;

// The case_num for the different position of the food area, adjustable variables in the Pheromone terminal
// For the case_num in the terminal 1 is top, 2 is middle and 3 is bottom
int case_num = atoi(argv[4]);

// The phero_r is for the radius of the food area, also adjustable in the pheromone terminal
int phero_r = atoi(argv[5]);

// I have replaced the influence condition as adjustable
float influence = atoi(argv[6]);

// To seperate the screen into three zones
int margin = 100;

// Added a new judgment statement for the system
for (int i = 0;i<numBots;i++)
{
    if (client->getID(i) == leaderID){
        pherofield[0]->addTo(client->getX(i)*imageWidth/arenaLength,client->getY(i)*imageHeight/arenaWidth,i,pheroStrength,20);
        leader = i;
    }
    else{
        int temp_y = imageHeight/2;
        int temp_x = (imageWidth-2*margin)/2*(case_num-1) + margin;
        pherofield[0]->addTo(temp_x,temp_y,i,pheroFoodStrength,phero_r);
    }

}
```

Appendix 2: The new method used in this thesis.

```
// Added a Stop_Threshold for the other robots to stop once they reaches the food area
#define Stop_Thr 174

// Then we need to add the command for the followers to stop moving when they reach the food
#define Stop_Thr 174

if(light_left > Sotp_Thr && light_right > Stop_Thr)
{
    Mortors(STOP, STOP);
    while(light_left >= Stop_Thr || light_right >= Stop_Thr)
    {
        LED_Top = 1;
        delay_ms(500);
        LED_Top = 0;
        delay_ms(500);
        light_left = read_adc(Left_Light);
        light_right = read_adc(Right_Light);
    }
}
```

Appendix 3: The method to control the followers to stop when it reaches the food foraging area.

```
// Adding the windEffect structure in the CPheroField.cpp file
// We need to add a new conditions into the original code with int windStrength as:
CPheroField::CPheroField(int wi,int he, float evapor,float diffuse,float influ, int iScale, int windStrength)
{
    // In this section where Taylor added a couple conditions into the structure
    // The algorithm he used to program in this part originally is to calculate the inactive swimming pool
    // water evaporation rate.
    float pw = 0.88; //This is the saturation vapor pressure at the water temeprature
    float pa = 0.5; // This is the saturation vapor pressure at the air dew point
    float a = 90.1; // This number is depends on the experimental setting calculation
    float b = 35.8; // The same as above
    float y = 92.8; // This is the latent heat of water at the pool temperature

    switch(windStrength){
        case 1:{
            // This controls uses the setting for the evaporation to divide the value of the evaporation rate
            // to generate the wind effect (linear)
            evaporation = evapor/(((a + b * 4)*(pw-pa))/y);
            break;
        }
        case 2:{
            evaporation = evapor/(((a + b * 8)*(pw-pa))/y);
            break;
        }
        case 3:{
            evaporation = evapor/(((a + b * 12)*(pw-pa))/y);
            break;
        }
        case 4:{
            evaporation = evapor/(((a + b * 16)*(pw-pa))/y);
            break;
        }
        case 5:{
            evaporation = evapor/(((a + b * 24)*(pw-pa))/y);
            break;
        }
        case 6:{
            evaporation = evapor/(((a + b * 32)*(pw-pa))/y);
            break;
        }
        default:{
            evaporation = evapor/(((a + b * 0)*(pw-pa))/y);
            break;
        }
    }
}
```

Appendix 4: The wind controlling method and the wind strength number.

```
// Then some modifications in the main Phero.cpp file
//Making the windEffect easy to adjust by using the case number
int windEffect = atoi(argv[3]);

// Adding the windEffect into each pherofield
pherofield[0] = new CPheroField(imageWidth,imageHeight,evaporation,0.1,influence,pheroScale,windEffect);
pherofield[1] = new CPheroField(imageWidth,imageHeight,0.1,0,1,pheroScale,windEffect);
pherofield[2] = new CPheroField(imageWidth,imageHeight,0.1,0,-5,pheroScale,windEffect);

//Recompute the pheromone decay with wind
wind = pherofield[0]->recompute(wind, windEffect);
```

Appendix 5: The pheromone modifications in this thesis.

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